E-TERRA LLC

Collecting and Processing Hi Resolution Satellite Imagery in Rural Areas of Alaska

An Alaska Aviation Safety Project Findings Report

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Introduction

The intent of this paper is to document the challenges and methods used in collecting and processing high resolution (1 meter or better) satellite imagery in rural areas of Alaska. The report documents work performed and conclusions made by the Alaska Aviation Safety Project (AASP), a research project jointly funded by NASA and the State of Alaska and administered by the Department of Military and Veterans Affairs (DMVA) of the State of Alaska.

The Alaska Aviation Safety project started in 2001 where the AASP helped define the Area of Interests (AOI's) of twelve remote mountain passes in Alaska as part of the NASA data buy (ref.). In conjunction with other areas, approximately 72K sq. km of IKONOS imagery (1m resolution) and IFSAR DEM data (10m postings) of remote mountainous areas were collected and distributed by NASA and processed by the AASP. Subsequently, approximately 90K sq. km of Quickbird and IKONOS imagery have been acquired and processed as part of Phase 2 of the AASP as shown in Figure 1.

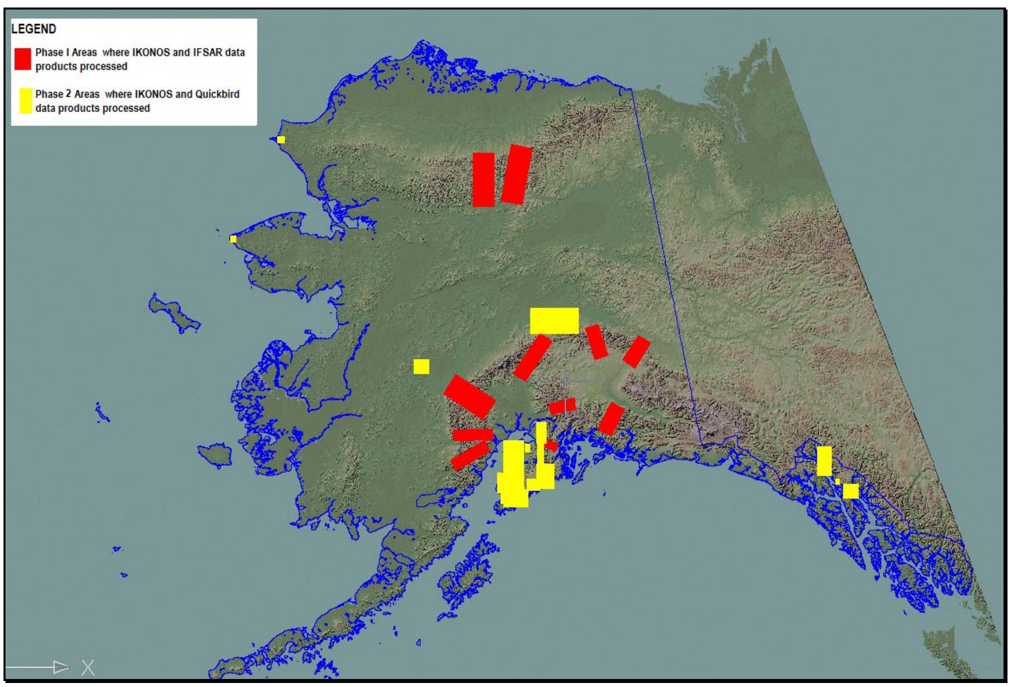


Figure 1.

As part of research conducted by the AASP, all of the imagery and DEM data acquired were utilized in a variety of 3D visualization packages with the intent of providing training level datasets to support aviation safety in Alaska. These datasets were and continue to be readily utilized by a non-profit Alaskan aviation safety and training organization, the Medallion Foundation, which has incorporated the datasets into their statewide network of flight simulators. As Alaska has a high dependence on aviation and is characterized by remote and mountainous areas, providing accurate photorealistic training and flight simulation products has proven very beneficial.

While the AASP have utilized a variety of 3D visualization platforms and technologies, the Microsoft Flight Simulator program has been among the most successful. The latest release of MSFS is called FS-X, and is distinguished by its ability to display high resolution imagery at its native resolution instead of having to sample it to coarser resolution (4.8 m resolution or greater) as in previous versions. When creating photorealistic scenery for use in flight simulators, requirements of the imagery include the following: low seasonal or color fluctuations across adjacent image tiles, orthorectification to remove relief displacement, and georectification to register the image to a coordinate system. Accordingly, addressing these requirements in Alaska, the largest state in the union and without any accurate statewide coverage for DEM's, imagery, or ground control has resulted in many challenges to overcome. The challenges and lessons learned for acquiring and processing high resolution imagery in Alaska as part of AASP ongoing efforts will be discussed and documented in this paper.

Searching, Ordering, and Acquiring High Resolution Satellite Imagery

The AASP has acquired imagery through a variety of means and sources. The initial imagery and DEM data sets were provided through the NASA databuy under an aviation research only license. Additional imagery data sets have since been acquired either through the sharing of datasets from other government agencies where the original license agreement allowed it or was uplifted, or through the purchase of imagery from commercial vendors, specifically Digital Globe and GeoEye (formerly Space Imaging).

Ordering and acquiring high resolution imagery has many own challenges that bear mentioning. One main challenge is there is only limited coverage of imagery for Alaska in commercial satellite imagery vendor archives. In addition, just determining where imagery is available, what its collection attributes are, and the general visual qualities of the collected imagery is quite a time consuming process. Finally, determining and acquiring the best product available from a suite of products available from either satellite imagery vendors also presents many challenges. The following is some discussion of these challenges and how the AASP dealt with them.

As previously mentioned, as of 2007, there is only limited coverage of imagery for Alaska in both GeoEye and Digital Globes' archives. For example, neither archive has a continuous coverage of imagery along the main highway and railroad corridor between Anchorage and Fairbanks; the most populated and industrialized area of the entire state. In more common remote areas of Alaska, imagery coverage of acceptable quality is even sparser. Even though Alaska is favorably positioned geographically with a high revisit time for the satellites, higher priority collects outside of Alaska along with issues related to non-favorable climatic conditions, (clouds and smoke from fires) and short collection window (snow cover until late spring and low sun angles in early fall) have greatly reduced the areas in Alaska that have been collected with acceptable imagery.

Searching for Satellite Imagery

Determining where high resolution imagery is available in Alaska, what its collection attributes are, and the general visual qualities of the collected imagery is a difficult and time consuming process. For researching the availability and quality of imagery, the AASP utilized proprietary image search tools available only to GeoEye and Digital Globe resellers. Even using these toolsets, many difficulties were encountered which ranged from inadequate filter and criteria to poor or lack of image chip preview. For example, since cloud coverage and image quality are both computed automatically, often the image chip needs to be visually reviewed to see the actual location and percentage of clouds to see if the image is acceptable. In the GeoEye's image search tool, the preview image chip was of insufficient pixel size to effectively review the product. In addition, both vendors' image search applications suffered from general crashes, glitches, and poor performance.

As these applications mature and become more developed, it is hoped that better search tools become available. For searching imagery in Alaska, some additional filter criteria that would be useful include the following: a seasonal date filter so that the winter or snow covered months can be included or excluded from the search. Another improvement for the vendor's image search tools is better background map data as the very coarse land/ocean boundary data displayed in Alaska is totally inadequate for generating Area of Interest (AOI) polygons. The AASP often utilized its statewide coverage of Landsat 7 imagery to create and confirm the location of AOI polygons.

Ordering Satellite Imagery

Product Type and Level

Ordering satellite imagery is a complicated and challenging task for a variety of reasons including uncertain needs, and a multitude of product choices. The following is a discussion of these challenges and information for dealing with them.

Picking a specific product type that meets all short term and long needs is difficult because these needs are often changing or incompatible. Also, some long term needs may be unknown until after the imagery is purchased, and in some cases ordering a specific imagery product means it will not work for a different use later. One way of dealing with this challenge is to purchase imagery in a bundled 16 bit format from the satellite vendor with the plan that consumable products would be created from it on an as needed basis. This typically means ordering imagery with minimal terrain and color corrections applied to it. One benefit of ordering bundled imagery is that most future needs can typically be supported by the initial purchase since it is the source information. The downside is that in the additional image processing services must be performed in the short term before a useful image product is available.

Image accuracy is one example of where short term and long term needs may or may not be met with a single image product. Typically, lower cost, lower accuracy, satellite ortho-imagery is purchased during the planning phase of projects. Then during future design phases of the projects, high accuracy ortho imagery is needed which cannot be typically derived from the original purchased imagery, and the satellite imagery must be purchased again or acquired through different means.

One requirement of ordering satellite imagery involves choosing a specific single product from a wide range of products and processing options available from the satellite vendors. Regardless of the vendor, satellite imagery products vary according to the type of processing, AOI geometry, and corrections performed on them. Some types of image processing and corrections a customer must choose from include the required product accuracy, level of terrain correction, level and type of color correction, image format, band format, coordinate system and others. As mentioned previously, the final choice of image product options can directly affect the ability of image to meet future needs, so choose wisely.

Another requirement when ordering image products involves choosing whether to order the imagery as a scene-based or nonscene-based product. A scene is a fixed area in size of roughly 12x12km, for IKONOS, or 16x16km, for Quickbird, that the image is acquired and delivered at. There are pros and cons of both product types which are discussed below.

Scene based products are designed for users with experience in advanced image processing techniques and require a minimum order of at least one scene, or 121 to 272 sq. km, or approximately $6000 per scene. Higher accuracies are possible with the scene based products if at least 6 well defined and evenly distributed ground control points (GCPs) per scene (Ref 5) are available and the rigorous method of geometric correction is used. Some cons of scene based products include non-flexible order areas, larger minimum order size, a GCP requirement and costs if high accuracies are desired and increased complexity of image processing tasks.

Non-scene based image products are fundamentally different from scene-based products in that they can be any irregular shaped polygonal area, and can span multiple over scenes. Non-scene based products are defined by the customer using an Area of Interest (AOI) polygon which defines the specific geographic areas they are interested in instead of having to order a whole scene. AOI polygons are typically custom drawn on a map so the customer can define their order while also incorporating desired local boundaries or land features or minimizing unwanted features such as large water bodies. A minimum AOI area of approximately 25 sq. km for Quickbird and 49 sq. km for IKONOS is required for imagery already in an existing archive. Non-scene based image products are capable

As previously described, the AASP recommends ordering high resolution satellite imagery that has not been corrected for terrain relief or color from the satellite vendors, and developing all future products from it. Specifically, we recommend purchasing the following products:

- Quickbird: Ortho Ready Standard, Bundle, 16 bit, Bilinear, DRA off

- IKONOS; Geo Ortho Kit, Bundle, 11 bit, Bilinear, DRA off

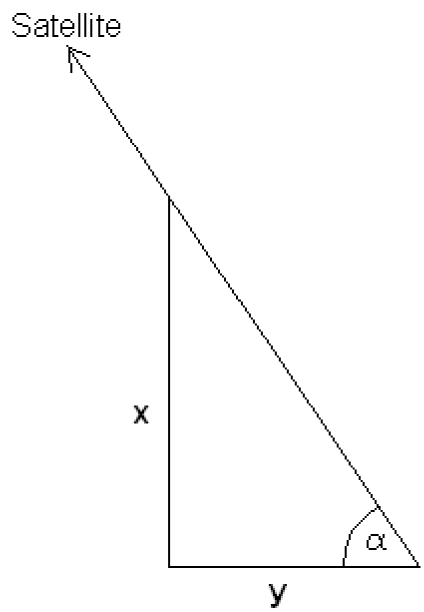
Other considerations for ordering

Influence of DEM Errors and Satellite Elevation Angles on Positional Accuracy

There is a geometric relationship between a DEM error (x) and the resulting positional error (y) in an orthorectified image, which depends on the satellite elevation angle (α).

y = x / tan α

Especially in areas of high relief and low DEM accuracy, it would be desirable to use images with close-to-nadir view angles (if available) to minimize this positional error.



Base Elevation of Ortho-Ready Image Products – Need for Overlap Between Adjacent Order Areas

It is recommended to let adjacent order areas for ortho-ready products overlap to prevent gaps in the final coverage due to shifts of the borders during orthorectification.

Ortho-ready Quickbird and IKONOS products are delivered rectified to a base elevation. This means a plane parallel to the earth ellipsoid has been used in the rectification instead of an actual DEM of the order area (Jacobsen 2001). In the not yet orthorectified image, areas above the base elevation are shifted in one direction while areas below base elevation are shifted in the opposite directions. These shifts depend on the viewing geometry of the individual images, with the satellite azimuth angle determining the direction of the shift and the satellite elevation angle influencing the amount of the shift. Using the average elevation in the order area as base elevation (which is the default for these ortho-ready products) minimizes the amount by which points in the ortho-ready image can be offset from their true position.

Still, in some high relief areas in Alaska, there may be very large differences between the average elevation and the elevation extremes in one order area. As an example, a vertical difference of 800 meters (e.g. a mountain top that is 800 meters higher than the average elevation of the area), combined with a satellite elevation angle of 70°, results in a horizontal offset of ca. 291 meters in the ortho-ready product. (Assuming that the average elevation in this area is 800 meters and the absolute elevation of the mountain top is 1600 meters, the offset would be twice as large if a zero elevation had been used as base elevation for the ortho-ready product.)

It has to be kept in mind when drawing the borders of an order area or AOI that the ortho-ready product still contains these shifts. The borders of the image areas can shift by up to several 100 meters (depending on the relief and the satellite elevation angles) during orthorectification. The position of the borders of the final ortho-product will thus be different from the borders of the order polygon. This is important especially when ordering data adjacent to another order area, where unintended gaps can open up between the orthorectified products even though the AOIs and ortho-ready products had precisely matching borders.

Color Depth – 8 bit vs. 16 bit

Both Quick Bird and Ikonos data are collected with a dynamic range of 11 bit (up to 2048 different gray values per band). The products are delivered either with 16 bit channels including the full dynamic range or scaled down to 8 bit (up to 256 different gray values). Quickbird data which had been automatically scaled down to 8 bit by DG often exhibited a lack of color depth, especially when there was a low sun elevation angle. The actual range of values in each band was much smaller than 256, the histograms showing 99% of the pixels sharing as little as about 20 different values per band (figure 3). The corresponding unenhanced image is very dark, and when the histogram is stretched during color balancing, homogeneous patches with a lack of texture become visible in some image areas (figure 4). When the same imagery is ordered as 16 bit data, the histograms are also relatively narrow, with the range of actual values being less than 10 % of the theoretical range of 2048. But the absolute range is now big enough to manually create 8 bit imagery with an acceptable color depth from these data (figures 3 and 4).

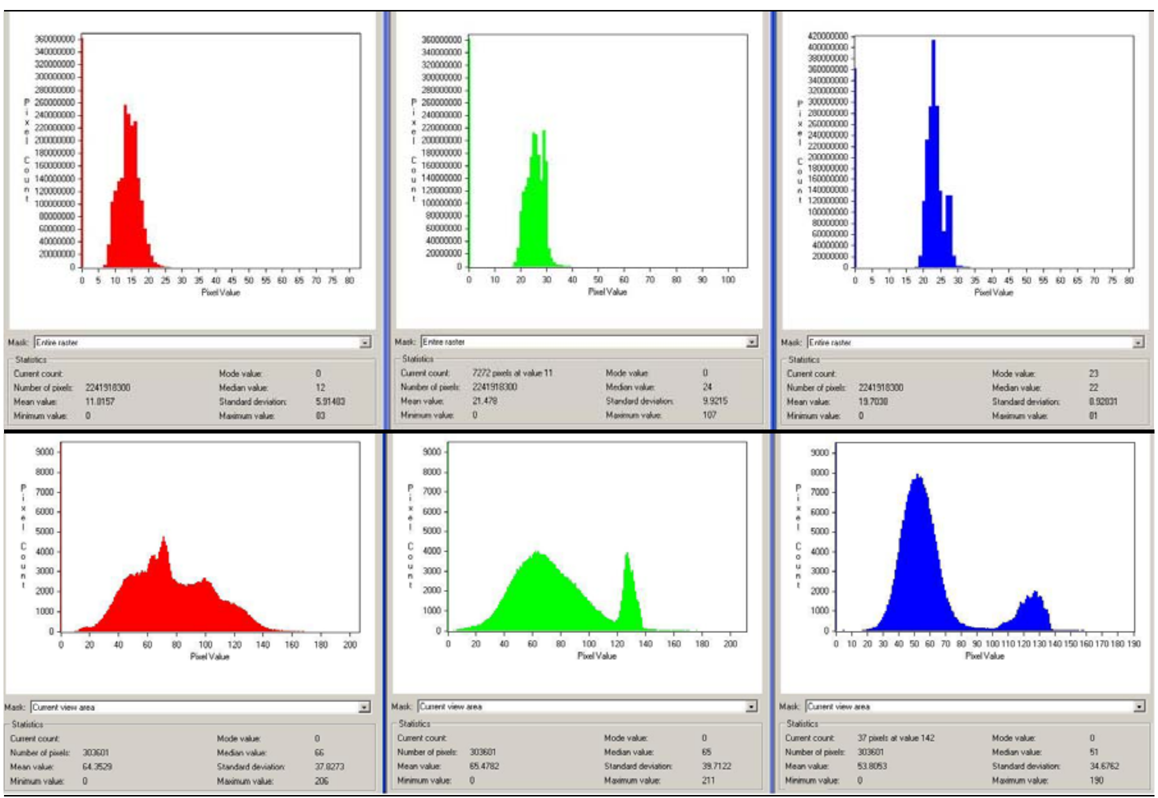


Figure 3: Histograms for Quickbird bands delivered as 8 bit data (above) and scaled to 8 bit manually from 16 bit data (below).

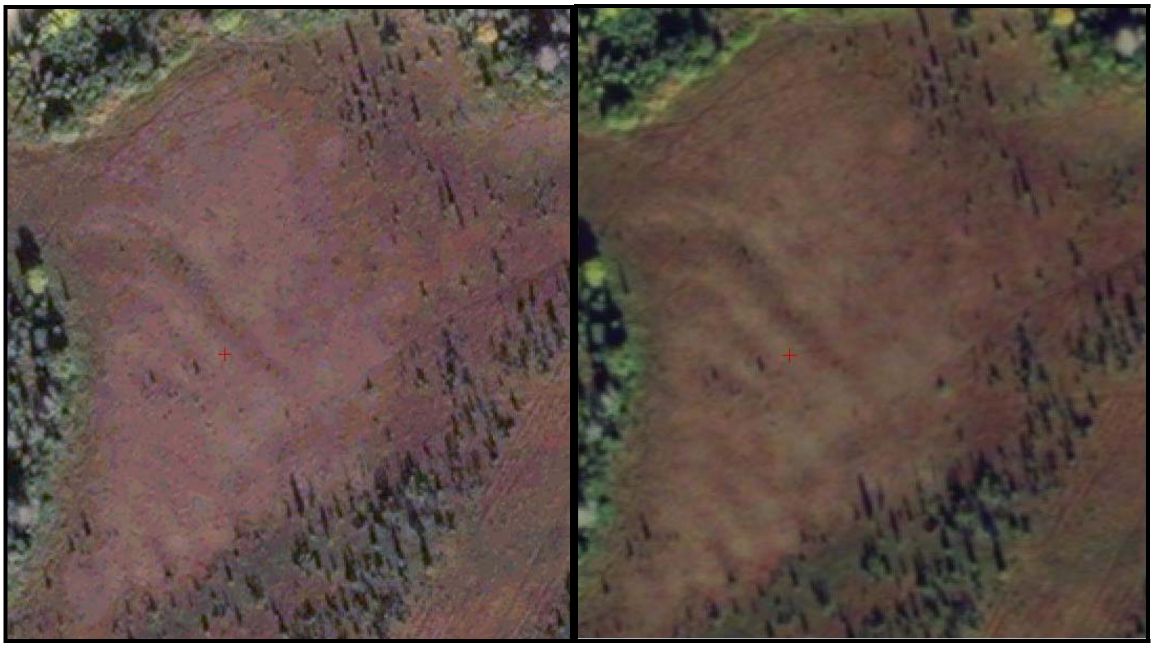


Figure 4:

Simple linear grey level scaling of the data from 16 bit to 8 bit (minimum value to 0, maximum value to 255) is not always a good solution as a few very high values (e.g. snow, ice, highly reflective buildings or clouds) can increase the absolute range of the data considerably while the large majority of the values have a much smaller range. Preserving some brightness differences even on snow surfaces while not reducing the contrast in the rest of the image too much requires non-linear scaling approaches.

Issue with Diagonal QB Collects

Orthorectifying some ortho-ready Quickbird products from diagonal collects gave unusable results with strong local artifacts (figure 5). Digital Globe acknowledged problems with RPCs for some of their strip based diagonal collects. They were not able to produce an ortho-ready standard product with correct RPCs for the diagonal collect in question and ended up delivering a scene-based product orthorectified by DG.

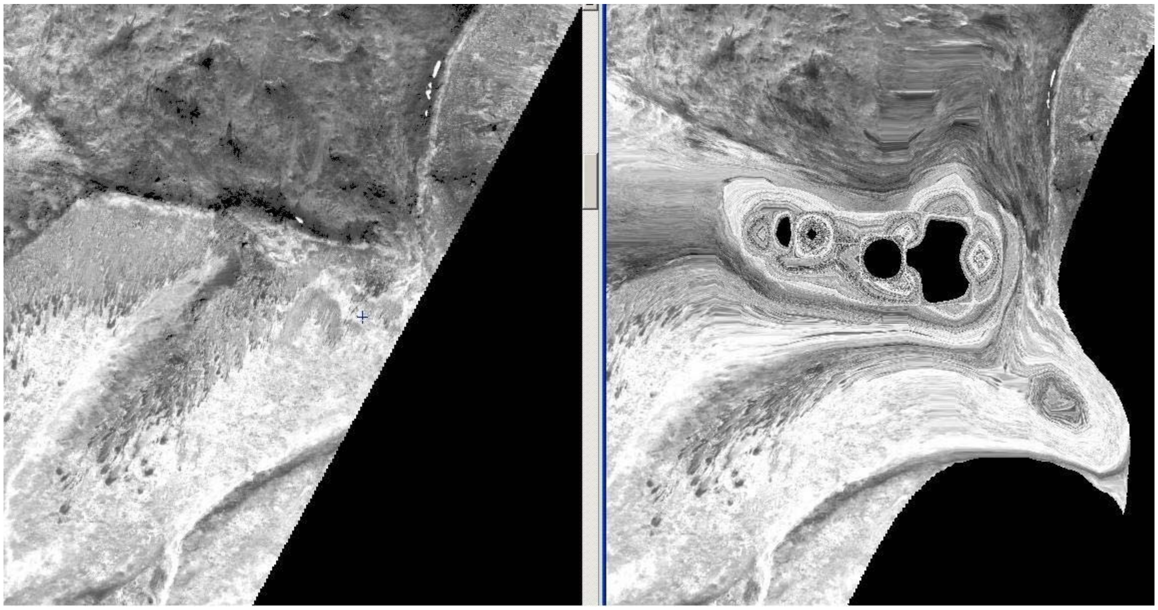


Figure 5: Diagonal Quickbird image with defective RPCs for the panchromatic band. The figure shows a detail of the ortho-ready image (to the left) and the same area after orthorectification using rational functions (to the right).

Processing High Resolution Imagery

Rectification

High resolution imagery, such as IKONOS (1m resolution), Quickbird (0.6m resolution), and SPOT (2.5-5.0 m resolution) need to be geometrically processed (orthorectified) with digital elevation models (DEM) and ground control points (GCP) to create high precision map products.

After orthorectification without ground control points, satellite imagery is typically accurate from 5 to 50 meters based on known orbital parameters and onboard position and attitude sensors, and an accurate DEM. Using quality ground control points, satellite imagery can achieve accuracies of 1-2 meters or better.

Positional inaccuracies due to lack of ground control can also affect the visual quality of the resulting ortho-image. For example, if a road is bordered by a steep embankment, high cliff etc., and the image is offset so that the road ends up where the DEM shows a steep slope, the road in the resulting ortho-image will appear smeared / distorted (figure 6).

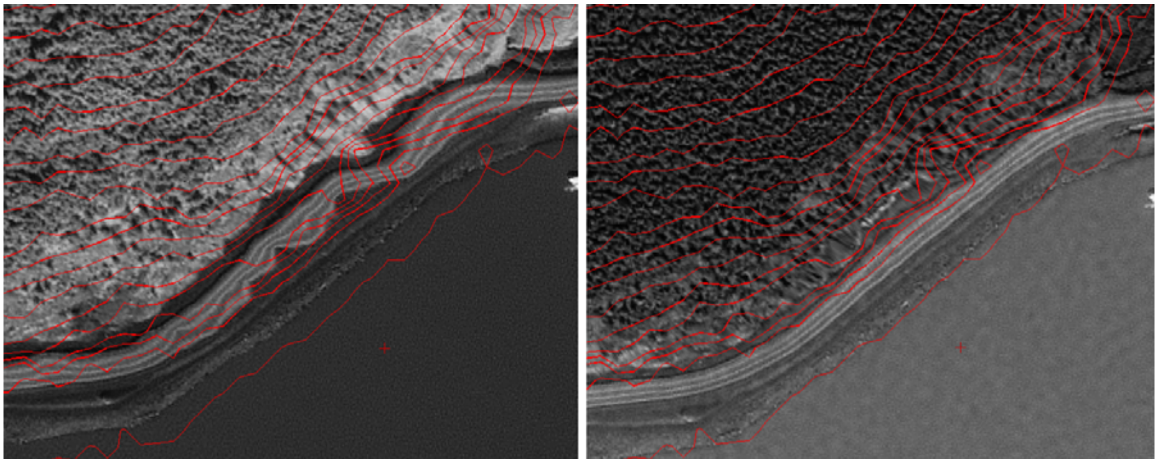


Figure 6: Road below cliff in Ikonos image. Left: orthorectified without ground control. Right: orthorectified with ground control points. Red lines are contours derived from the IFSAR DEM used in the orthorectification.

Use of Rational Functions

Ortho-ready IKONOS and Quickbird images can be orthorectified using rational functions extracted from the RPC files (rational polynomial coefficients) that are delivered with the imagery. It is possible to use this method without ground control.

Experiences using this method to orthorectify IKONOS imagery at E-Terra (Denali East and Portage) suggest that the resulting imagery usually has positional errors between 5 meters and 15 meters, in some cases up to 30 meters (aside from effects of large DEM errors). Ortho-ready Quickbird imagery rectified based on the RPC files alone (e.g. Kenai West imagery) mostly had errors between 5 meters and 25 meters, and several images had errors beyond that, the extreme case being the southern end of a long image which was offset from the road centerline control data by around 80 meters.

The orthorectification accuracy can be improved using GCPs to refine the math model with a polynomial adjustment. PCI Geomatics recommends using 1 or more GCPs (and zero-order RPC adjustment) for the IKONOS Ortho Kit and a minimum of 3 GCPs (and first-order RPC adjustment) for ortho-ready Quickbird images.

For a rectification of ortho-ready imagery using rational functions, the math model with its RPCs can also be computed completely from GCPs instead of being extracted from the image RPC file. This needs a minimum of 5 GCPs per image, with 19 GCPs per image being recommended by PCI.

The alternative to these empirical RPC methods is the rigorous physical method (satellite orbital modeling). A satellite rigorous model has been developed by Thierry Toutin for the Basic Imagery products of IKONOS, Quickbird and other satellites. Like the RPC method, it is implemented in the Geomatica OrthoEngine software. It is also possible to correct Ortho-Ready Standard Quickbird imagery using Toutin's rigorous model, although more GCPs (at least 8 vs. 6 for Basic QB Imagery) are required to achieve an accurate model (Cheng et al. 2003). PCI Geomatics recommends using 10 to 15 GCPs per image for satellite orbital modeling. (This method has not been tested at E-Terra yet.)

As discussed in later in this report (DEM comparison case study) and also by Putman, W., Worum, G., Lee, 2005, (Ref.. 2), the National Elevation Dataset (NED) in Alaska is out of date and inaccurate.

Challenges

1. DEM – Poor DEM accuracy, resolution, and quality.
    a. The NED in Alaska is only available on NAD 27 datum, while all other states have been using the widely accepted and more accurate NAD 83 datum. The NAD 27 datum in Alaska has many known and documented inaccuracies (reference PPT by NGA).
    b. The NED in Alaska is notoriously inaccurate. One such study in the Tanana Valley Alaska found errors up to __ ft between DGPS survey data and the NED (reference Putman, Worum Lee, 2005) In addition, studies performed by the AASP found discrepancies up to _ ft in south central Alaska
    c. Many of Alaska DEMS are out of date.
2. Lack of Ground Control – The State of Alaska does not have a publicly available library of ground control point.

Sampling Discussion – Introduction of Zero Values

The satellite images are delivered with a background value of zero and with actual image data pixels having gray values of 1 and above in each band. It is necessary to preserve a unique background value in order to be able to make the background transparent in the final product without creating holes in the image where pixels have the same value. When the images are re-sampled during orthorectification, the gray values can change slightly. Several re-sampling methods are available. Cubic Convolution produces visually good results, but the algorithm has a sharpening effect which introduces zero values in dark areas of the image. Bilinear Interpolation results in slightly less sharp (slightly blurred) images but does not introduce zero values where none were before. If using Cubic Convolution re-sampling during image processing to avoid blurring, special steps need to be taken to preserve a unique background value (i.e. set the background to a different unique value before processing or remove zero-values under a data mask after re-sampling).

Pan-sharpening Before or After Orthorectification?

A terrain-dependent shift between panchromatic and multispectral bands occurs in ortho-ready / standard geometrically corrected imagery (Quickbird as well as Ikonos). The shift depends on the vertical distance from the average base elevation / reference height. The panchromatic and multispectral images are not acquired simultaneously (see moving cars), resulting in slightly different view geometries.

[Example Portage Ikonos image po146558_0000000 (nominal collection elevation 67.9 degrees, nominal collection azimuth 272.7 degrees, reference height 509.97 m or 1673'): Approximately 1 m shift per 1000' or 300 m distance from reference height (base elevation).]

This impedes the result of pan sharpening before orthorectification for areas far below or above the average image elevation (reference height). On the other hand, orthorectifying the panchromatic and multispectral bands separately before pan sharpening may introduce new errors / differences if using GCPs which cannot be identified with the same precision in both the multispectral and the panchromatic image.

<u>Color Balancing</u>

Ground Control Specifications

The following is a specification for surveying ground control points for use with processing high resolution satellite imagery (1m or better) under a variety of areas in Alaska. This specification is based on work performed on and for use with the Alaska Aviation Safety Project.

Assumptions

1. The satellite imagery to be processed with the GCPs, or other digital imagery of the same resolution or better, has been previously acquired and is available to the survey contractor. The imagery can be provided in compressed and uncompressed digital form, as well as hard copy plots.

2. All proposed work would be performed under summer conditions, with little to no snow cover.

3. The number and general location of proposed GCPs will been provided to the survey contractor. The proposed GCP locations will be previously marked on the provided image by a qualified photogrammetrist.

Specification for GCP Survey

1. **Preplanning**
   A preplanning meeting estimated at 4-8 hours with the photogrammetrist will be required to discuss and review the proposed work. The meeting agenda should include the location and desired accuracy of the proposed GCPs, as well as site access methodology and issues.

2. **Ground Control Point (GCP) Collection**

   Location of GCPs

During the planning meeting, the location of proposed GCPs shall be provided, based on the analysis of existing digital imagery. It is anticipated that some proposed GCPs will be inaccessible or not located in the field. For these reasons, alternate GCP locations shall be discussed and or provided during the planning meeting.

For planning purposes, the following rule of thumb for locating GCPs can be used.

a. The GCPs shall be evenly distributed throughout the project or image area.
b. Some GCPs shall be located as close as possible to the edge of the project area.
c. The GCPs shall be located over whatever range of elevation is present in the project area.

During the field, the surveyed GCP location shall be located and marked as precisely as possible on the image. It is recommended that this task be performed looking at a digital image on a portable computer display, with full zoom and pan, and markup capabilities. Marking the GCP location on a hard copy printout of the image is acceptable, but not as desirable.

Acceptable Features as GCPs

The primary requirement of a GCP is that the physical ground feature being surveyed can be tied to a specific pixel in the digital image. In remote areas and 0.6-1 m resolution imagery, it can be challenging and time consuming to locate physical features that are distinguishable. Therefore, a list of recommended features along with general guidelines for selecting features for use as GCP is provided.

Some ideal qualities of GCP sites include features with a distinguishable intersection point that are surrounded by areas of contrasting colors. Features that have a symmetrical center, such as a rooftop, are also desirable. Items that should be avoided include features that are located in a shadow on the image, and mobile structures.

The following are physical features that are recommended as GCPs in 1m or better digital imagery.

- Center of rooftops or ground polygons
- Visible building and roof corners, platforms
- Paint stripes along roads or parking lots
- Curb or trail intersections/corners
- Distinct fence line intersections
- Culverts
- Bridges
- Trees
- Bushes
- Rock outcrops
- Wetlands
- Creeks
- Benches
- Signs
- Utility poles

- Pipelines
- Archeological sites

Figure 7. Example Ground Control Point.

GCP Accuracy Requirements

GCP accuracy has been proven to greatly impact the accuracy of high resolution satellite imagery when they are used during geometric correction processes (Ref 1). At a minimum, survey grade DGPS equipment and processing methods are recommended. The following is the requested GCP accuracy for use with 1m or better satellite imagery.

Horizontal Accuracy: 20 cm (CE95)
Vertical Accuracy: 30 cm (CE95)
Decimeter accuracy is appropriate when the ground sample distance of the imagery is less than 1-meter

Following the field survey, an accuracy assessment should be provided to demonstrate the horizontal and vertical accuracies for each point collected.

GCP Coordinate Systems

GCP coordinates should be delivered in one or more of the following coordinate systems:

- State Plane Coordinates (including zone), NAD83 reference datum, with Mean Sea Level elevations referenced to or Heights above Ellipsoid elevations, or NAVD88 vertical datum.

- Geographic Coordinates (decimal degrees), referenced to WGS84 datum, with Mean Sea Level referenced to Heights above Ellipsoid elevations, or NAVD 88 vertical datum.

- Universal Transverse Mercator (UTM), (including zone), NAD83 reference datum, with Mean Sea Level elevations referenced to or Heights above Ellipsoid elevations, or NAVD88 vertical datum.
- Elevation units must be specified as either US survey feet or Meters

GCP Naming Convention

The GCPs shall all be numbered according to a standard convention, which includes a single letter prefix followed by a sequential integer (Ref. 2). The letter prefix shall reference a specific field book used during the survey. A different letter prefix shall be used for different field books.

Examples of Naming Convention:
A1, A2, etc. - (field book 1)
B1, B2, etc. - (field book 2)

Project Deliverables

1. **ASCII File:** A coordinate file (text or spreadsheet) in ASCII Comma, TAB, or Space Delimited with the following information on each line for each GCP:
   - Point ID (text field)
   - X Coordinate or Longitude (numeric field)
   - Y Coordinate or Longitude (numeric field)
   - Elevation (numeric field)
2. **Metadata File:** Information about the survey must be included in a separate ASCII file:
   - Coordinate System (State Plane, Geographic, UTM)
   - State Plane or UTM zone, if applicable
   - Horizontal datum (NAD83, WGS84)
   - Horizontal Units (US Survey Feet, Meters)
   - Vertical Datum (Height above WGS84 Ellipsoid, NAVD88,)
   - Vertical Units (US Survey Feet, Meters)
   - Estimated horizontal and vertical accuracy of each GCP (CE90, CE95, or RMSE)
3. **Project Report:** A project report describing the equipment and procedures used to collect and process the desired GCP, as well the datum and coordinate system used. Any significant observations from the field work such as severe climactic conditions, or office processing tasks should be included.
4. **Overview Map**: The GCP locations shall draw on a photo or image chip showing all GCP locations. This data can also be provided as a GIS data shapefile such as a shapefile or Autodesk Map DWG file.

5. **Site Sketch:** A hand-drawn site sketch of each GCP and associated field notes including date and time of data collection. Information concerning nearby landmarks as well as how the GCP was located on the photo and in the field should be included.

6. **Site Photos:** Photos of the GCP location will aid in identifying the GCP in the imagery. At least two photos taken from different directions should be taken. The GCP number should be apparent in each photo provided. The direction the camera was facing should be recorded and available for each photo.

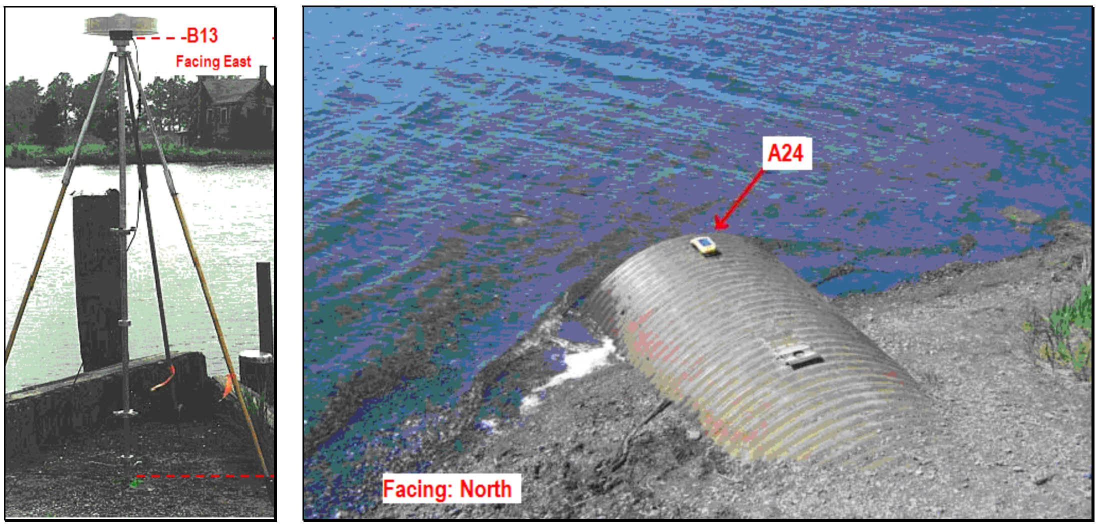


Figure 8. Example Photos of GCP point.

7. **Project DVD:** A copy of all coordinate and image data and project reports shall be delivered on DVD.

Case Studies

The Portage Test Area

The Portage test area is one of the AASP mountain pass areas which are covered by Ikonos data and IFSAR elevation data sets. It covers approximately 740 km² around 60°50'N, 148°50'W, including the eastern end of the Turnagain Arm with the Seward Highway up to Turnagain Pass, the Portage Pass with Portage Lake and Glacier, Whittier and parts of the Passage Canal and Blackstone Bay.

The IFSAR dataset is a 10 meter resolution digital surface model. The product was derived using the Intermap Technologies STAR-3i airborne interferometric SAR data acquisition system. According to Intermap metadata, the X-band Synthetic Aperture Radar (SAR) data was acquired on July 29 2001. The flying height was 30,000 feet Above Mean Ground. The primary look direction was south; the alternate look direction was east. Areas of missing data were interpolated using continuous curvature spline over non-data areas. Significant bodies of water were assigned an elevation which corresponds to the shoreline.

As the rest of the State, the area is also covered by the NED (National Elevation Dataset) 2 are second resolution DEM.

The Portage Ikonos data consists of two images (with two tiles each), both acquired on September 3 2002, delivered as standard geometrically corrected PAN/MSI bundle (Ortho Kit with RPC files). Map Projection and Datum: UTM6 WGS84, pan resolution 1 meter. Nominal collection elevation 67.9° and 68.8°, nominal collection azimuth 272.7° and 303.5°.

There is also a Quickbird image from a later AASP phase which overlaps with this test area, covering the Turnagain Arm area (and continuing north to Eklutna Lake). It was acquired on 25 June 2004, delivered as standard ortho ready bundle product, State Plane Zone 4, NAD83, pan 0.6 meter resolution. Base elevation 676.62 meters; mean satellite elevation 76.8°, mean satellite azimuth 274.8°.

CASE STUDY 1

Portage IKONOS Orthorectification Using Different Numbers of GCPs

Reducing the number of GCPs from 22 to 0 in a random order, and using the unused GCPs as additional ICPs, the ICP residual error becomes smaller with fewer GCPs, and the lowest ICP error is achieved with just one good GCP and zero-order RPC adjustment (table 5). Having just one GCP however, the result is of course very dependent on the quality of that one Control Point. Using a different single GCP, the ICP residual error (SQRT ($RMSX^2+RMSY^2$)) was 3.39 instead of 2.1 meters, and was improved by adding two or three more GCPs.

Table 1: Residual errors with different numbers of GCPs and ICPs (and 17 Tie Points). DEM used: IFSAR.

		Zero-order RPC adjustment					First-order RPC adjustment				
No. of GCPs	No. of ICPs	GCP X RMS	GCP Y RMS	ICP X RMS	ICP Y RMS	ICP Res	GCP X RMS	GCP Y RMS	ICP X RMS	ICP Y RMS	ICP Res
22	11	1.06	0.77	**2.42**	**1.96**	**3.11**	0.83	0.68	**2.19**	**2.01**	**2.97**
16	17	0.99	0.85	**2.12**	**1.61**	**2.66**	0.79	0.67	**1.9**	**1.68**	**2.54**
10	23	1.09	0.93	**1.83**	**1.39**	**2.30**	0.81	0.74	**1.68**	**1.46**	**2.23**
8	25	1.02	0.95	**1.79**	**1.33**	**2.23**	0.79	0.83	**1.68**	**1.34**	**2.15**
6	27	0.82	1.13	**1.83**	**1.3**	**2.24**	0.72	0.94	**1.74**	**1.29**	**2.17**
5	28	0.48	1.15	**1.75**	**1.27**	**2.16**	0.48	0.98	**1.69**	**1.31**	**2.14**
4	29	0.43	1.28	**1.74**	**1.29**	**2.17**	0.24	0.7	**1.7**	**1.73**	**2.43**
3	30	0.51	1.39	**1.72**	**1.45**	**2.25**	0.3	1.03	**1.65**	**1.4**	**2.16**
2	31	0.75	2.05	**1.68**	**1.48**	**2.24**					
1	32	0.48	1.69	**1.64**	**1.31**	**2.10***					
0	33	N/A	N/A	**2.74**	**9.1**	**9.50**					

* Result for a good single GCP, ICP Res was 3.39 for a different single GCP (see text above).

The reduction of errors with reduced numbers of GCPs in table 5 is also a function of having more (and on average more accurate) ICPs available for the accuracy assessment. If the same (generally lower quality) 11 ICPs are used to determine the accuracy, the ICP residual error is much higher for small numbers of GCPs, and the error is reduced when the number of GCPs is increased (table 6).

Table 2: Residual errors with different numbers of GCPs, 11 ICPs (and 17 Tie Points). DEM used: IFSAR.

		Zero-order RPC adjustment					First-order RPC adjustment				
No. of GCPs	No. of ICPs	GCP X RMS	GCP Y RMS	ICP X RMS	ICP Y RMS	ICP Res	GCP X RMS	GCP Y RMS	ICP X RMS	ICP Y RMS	ICP Res
22	11	1.06	0.77	**2.42**	**1.96**	**3.11**	0.83	0.68	**2.19**	**2.01**	**2.97**
16	11	1.44	2.47	**3.36**	**2.93**	**4.46**	0.81	2.31	**1.76**	**3.68**	**4.08**
10	11	1.69	3.05	**3.28**	**2.84**	**4.34**	1.03	2.31	**1.76**	**3.83**	**4.22**
8	11	1.77	3.3	**3.26**	**2.92**	**4.38**	1.07	2.59	**2.1**	**3.69**	**4.25**
6	11	1.64	3.57	**3.39**	**3.37**	**4.78**	0.94	2.3	**2.29**	**3.75**	**4.39**
5	11	1.86	3.87	**3.44**	**3.43**	**4.86**	1.06	2.54	**1.94**	**3.68**	**4.16**
4	11	1.59	3.56	**3.86**	**4.19**	**5.70**	1.1	2.64	**2.01**	**3.89**	**4.38**
3	11	1.86	4.31	**3.77**	**4.15**	**5.61**	1.44	3.82	**2.13**	**3.1**	**3.76**
2	11	2.36	4.97	**3.69**	**4.21**	**5.60**					
1	11	0.71	1.11	**4.35**	**6.33**	**7.68**					
0	11			**4.19**	**10.88**	**11.66**					

Generally, for the IKONOS orthorectification, first- or second-order RPC adjustments did not lead to consistently or significantly better results than the zero-order RPC adjustment, and they need more GCPs.

Conclusion: When ortho-rectifying IKONOS Geo Ortho Kit data, using GCPs to adjust the RPCs will improve the resulting positional accuracies significantly. A single good GCP and zero-order RPC adjustment can already lead to optimal results (in this example, RMS errors are well below 2 meters in both the X and Y direction, as determined by 32 ICPs). With GCPs of uncertain quality or imprecise identification in the image, using a larger number of GCPs may be beneficial to reduce the influence of inaccuracies in individual control points.

CASE STUDY 2

Portage Quickbird Orthorectification with and without Ground Control

The ortho-ready Standard Quickbird image which was available for this area (overlapping with the IFSAR DEM and the collected Ground Control Points) was 75 kilometers long from North (Eklutna) to South (Turnagain Pass). Orthorectifying it with rational functions based on the RPCs delivered with the image resulted in unusually large positional errors compared to most other ortho-ready Quickbird images. The errors were moderate in the north, but reached 75 to 90 meters in the south (the area looked at here), pointing to imprecise RPC values. The RMS errors found when running RPC-based orthorectification tests with this image are thus probably generally higher than they would be for the average ortho-ready Quickbird image.

Orthorectification tests were run using the panchromatic ortho-ready Quickbird image. 15 of the 22 GCPs and 9 of the 11 ICPs used in the IKONOS orthorectification tests were usable with this image, all located in the southern part of the image. No Tie Points were involved, since this is a single image with a single RPC file.

Without GCPs, the ICP residual error (SQRT $(RMSX^2+RMSY^2)$), determined using all 24 available control points, was 87 meters. Using 1 GCP (the same one that led to the good results with the IKONOS data) the IPC residual was still 12 meters. Using zero-order RPC adjustment, the ICP residual error decreased with more GCPs, but never got below 5 meters even with all 15 GCPs (tables 7 and 8). Much better accuracies were achieved with first-order RPC adjustments or, if using at least 7 or 8 GCPs, with second-order RPC adjustments. Table 7 shows the results for a random reduction of GCPs from 15 to 0 (in the same way as table 5 for the IKONOS test). Table 8 shows the results of choosing the GCPs to be as well distributed as possible in this case (i.e. aiming to have the first GCPs in the corners of the area which contained all of the control points). This clearly improved overall results. Using four well-distributed GCPs and a first-order RPC adjustment resulted in an IPC residual error of 2.26 meters (less than 2 meters in both the X- and the Y-direction), which is close to the best accuracies achieved in the IKONOS orthorectification test.

Table 3: Residual errors for 0 to 15 GCPs, reduced without regard for their distribution.

		Zero-order adjustment					First-order adjustment					Second-order adjustment				
GCPs	ICPs	GCP X RMS	GCP Y RMS	ICP X RMS	ICP Y RMS	ICP res	GCP X RMS	GCP Y RMS	ICP X RMS	ICP Y RMS	ICP res	GCP X RMS	GCP Y RMS	ICP X RMS	ICP Y RMS	ICP res
15	9	5.35	0.95	**5.16**	**1.25**	**5.31**	1.31	0.53	**2.22**	**1.64**	**2.76**	0.5	0.44	**1.81**	**1.54**	**2.38**
12	12	5.92	0.95	**5.27**	**1.21**	**5.41**	1.48	0.57	**2.04**	**1.41**	**2.48**	0.42	0.47	**1.7**	**1.33**	**2.16**
10	14	6.42	0.84	**5.23**	**1.33**	**5.40**	1.63	0.59	**1.86**	**1.32**	**2.28**	0.38	0.44	**1.71**	**1.3**	**2.15**
8	16	6.25	0.74	**6.77**	**1.23**	**6.88**	1.72	0.61	**2.18**	**1.25**	**2.51**	0.22	0.42	**1.97**	**1.21**	**2.31**
7	17	6.36	0.65	**7.61**	**1.19**	**7.70**	1.46	0.57	**3.79**	**1.48**	**4.07**	0.02	0.44	**3.6**	**2.2**	**4.22**
6	18	5.91	0.69	**9.11**	**1.16**	**9.18**	1.46	0.62	**3.53**	**1.43**	**3.81**	0.02	0.42	**3.51**	**5.31**	**6.37**
5	19	6.59	0.65	**8.82**	**1.14**	**8.89**	1.13	0.33	**3.34**	**1.38**	**3.61**					
4	20	7.59	0.68	**9.81**	**1.14**	**9.88**	0.61	0.38	**3.84**	**1.34**	**4.07**					
3	21	8.87	0.78	**9.17**	**1.1**	**9.24**	0.49	0.0	**3.47**	**1.48**	**3.77**					
2	22	13.15	1.1	**11.63**	**1.79**	**11.77**										
1	23	13.14	0.78	**11.82**	**1.76**	**11.95**										
0	24	N/A	N/A	**86.85**	**5.3**	**87.01**										

Table 4: Residual errors for different numbers of well-distributed GCPs.

		Zero-order adjustment					First-order adjustment					Second-order adjustment				
GCPs	ICPs	GCP X RMS	GCP Y RMS	ICP X RMS	ICP Y RMS	ICP res	GCP X RMS	GCP Y RMS	ICP X RMS	ICP Y RMS	ICP res	GCP X RMS	GCP Y RMS	ICP X RMS	ICP Y RMS	ICP res
10	14	5.79	1.04	**5.14**	**1.13**	**5.26**	1.58	0.58	**1.95**	**1.31**	**2.35**	0.57	0.34	**1.46**	**1.28**	**1.94**
8	16	6.54	0.91	**5.11**	**1.14**	**5.24**	1.78	0.62	**1.84**	**1.2**	**2.20**	0.64	0.33	**1.36**	**1.16**	**1.79**
7	17	6.78	0.97	**5.65**	**1.11**	**5.76**	1.88	0.67	**1.86**	**1.16**	**2.19**	0.69	0.35	**1.32**	**1.12**	**1.73**
6	18	6.9	1.0	**5.3**	**1.08**	**5.41**	1.6	0.47	**2.06**	**1.18**	**2.37**	0.18	0.44	**3.6**	**2.2**	**4.22**
5	19	7.78	0.92	**5.22**	**1.11**	**5.34**	1.79	0.49	**2.0**	**1.14**	**2.30**					
4	20	9.11	1.06	**5.22**	**1.07**	**5.33**	2.06	0.52	**1.96**	**1.12**	**2.26**					
3	21	9.71	1.31	**7.92**	**1.03**	**7.99**	1.89	0.64	**2.3**	**1.09**	**2.55**					
2	22	10.07	1.86	**6.41**	**1.04**	**6.49**										
1	23	13.14	0.78	**11.82**	**1.76**	**11.95**										

Given enough (at least 7 well distributed) GCPs, second-order adjustments produced somewhat better results than first-order adjustments. However, there is a greater risk for creating large errors in areas without ground control points when using second-order adjustments (SOURCE PCI?).

The tests confirm the statements of (PCI Geomatics 2007, Toutin, Jacobsen) that **for Quickbird ortho-ready data at least 3 GCPs and a first-order RPC adjustment are needed** for good orthorectification results with rational functions improved by GCPs, while just one good GCP and zero-order RPC adjustment can suffice for IKONOS Ortho Kit data.

CASE STUDY 3

Dillingham-Aleknagik: Orthorectification of ortho-ready Quickbird imagery using rational functions computed from GCPs compared to rational functions extracted from the DG-provided RPC file (refined with GCPs)

In a project in co-operation with Mullikin Surveys the aim was to create an image of the road corridor from Dillingham to Aleknagik with the highest possible positional accuracy. The area of interest had a north-south extension of ca. 11 miles and an east-west-extension of ca. 3 miles. The road corridor as such was 4000 ft wide (2000 ft to each side of the road centerline). This was the area for which imagery was ordered.

A Quickbird image (Catalog ID 10100100049F3000, acquisition time 2005-10-31, mean sun elevation 16.6 degrees, mean satellite elevation 70.9 degrees, mean satellite azimuth 269.3 degrees, mean Off-Nadir View Angle 17.7 degrees) was the best available image for this area, although its acquisition parameters are less than ideal. The late October acquisition date and accordingly low sun elevation angle result in long tree shadows which darken part of the road. The off-nadir view angle is also higher than desirable for optimized positional accuracies. (This is the case for many of the Quickbird images in the archive). The image was initially ordered as a standard (coarse DEM rectified) product. However, it quickly turned out that the positional accuracy of this product was not good enough, and it was decided to order an ortho-ready standard product and to orthorectify it with an improved Digital Elevation Model (DEM).

Mullikin Surveys delivered a DEM with high precision along the road. This had been surveyed for an AK DOT project (road centerline and some points to the sides of the road). The resulting TIN was integrated into the surrounding NED data (?) and gridded with 50 ft resolution.

Mullikin Surveys also collected Ground Control Points (using a survey grade dual band receiver). Making the GCPs surveyed by the field crew usable for this project involved a learning process. There were initial difficulties with the identification of the surveyed points in the unrectified image. Getting a Mullikin staff member to mark the spots on the Quickbird image and getting a copy of the field book helped make most of the points usable. The field crew also went out there a second time and surveyed some more points in co-ordination with me, in areas of the imagery where there had been a lack of usable points before, and where suitable features (e.g. parking-lot markings) were clearly visible on the image. It would have been helpful to have a pre-planning meeting between the surveyors and the image processor, discussing methods and potential problems and jointly identifying possible suitable ground control points in the image that was to be rectified, before the actual field work started.

The Quickbird image was first orthorectified using the improved DEM and with rational functions extracted from the RPC file without any GCPs. This resulted in a large ICP (Independent Control Point) RMS error in the X direction of 27.25 pixels or 16.35 meters (much larger than the error in the Y direction because of the satellite azimuth of 269 degrees). The total ICP residual error of 16.46 meters is not within the specifications for Quickbird standard imagery (23 meters CE90). The same can be said about the coarse DEM Standard Product with a residual error of 19.54 meters. Anyway, this magnitude of error was definitely not good enough for the purposes of this project.

The math model was then refined with increasing numbers of GCPs. The use of GCPs to refine the rational functions extracted from the RPC file reduced the X RMS value by an order of magnitude (see table 5). However, the use of more than four GCPs and the attempt to increase the GCP quality did not lead to much better results. Improvements on one section of the road were usually paid for with deterioration somewhere else.

Table 5: Residual errors (in **pixels** of 0.6 meters) for Dillingham-Aleknagik QB Standard product and Ortho-Ready-Standard product orthorectification with improved DEM.

Math Model	No. of GCPs	No. of ICPs	GCP X RMS	GCP Y RMS	GCP Res	ICP X RMS	ICP Y RMS	ICP Res
DG Standard Product, coarse DEM rectified	0	8	n/a	n/a	n/a	32.39	3.39	32.57
Rational Functions from RPC file, adj.order 0	0	8	n/a	n/a	n/a	27.25	3.26	27.44
Rational Functions from RPC file, adj.order 0	4	4	2.26	0.67	2.36	3.11	4.19	5.21
Rational Functions from RPC file, adj.order 1	7	5	2.20	0.73	2.32	2.62	2.15	3.39
Rational Functions from RPC file, adj.order 1	8	3	2.27	1.53	2.74	1.99	3.86	4.34
Rational Functions computed from GCPs, 5 coefficients	11	2	0.25	0.46	0.52	0.98	2.47	2.66

Finally, 11 GCPs were used to calculate GCP-based rational functions and orthorectify the image without the RPCs provided by DG. This led to the best result. Dispensing with the DG-provided RPCs and calculating the rational functions based on GCPs alone reduced the GCP residual error markedly from around 1.5 meters to 0.31 meters and the IPC residual error to 1.6 meters (since there were only two – lower quality – control points left as ICPs in that case, the IPC RMS values are not very meaningful here, but comparing the orthorectified image to the road centerline vector showed a clear overall improvement). A minimum of 5 GCPs per image are needed to be able to use this method (with 3 coefficients), and PCI recommends using 10 coefficients, which would need 19 GCPs per image. The 11 GCPs that were available here would have made it possible to use 6 coefficients, but the result was better with just 5 coefficients and these GCPs.

Computing the rational functions from GCPs is not recommended by Cheng & Toutin (Cheng et al. 2003, Toutin & Cheng 2002). They judge this method to be instable and state that it is highly dependent upon the accuracy and distribution of GCPs. However, in this case the GCPs were obviously good enough to produce a better result than anything that could be achieved when the rational functions were based on the RPC file that came with the image.

(Mercer et al. (2003) achieved stable results for Ikonos and Quickbird orthorectification computing the rational functions from large numbers (over 20) of well distributed GCPs.)

CASE STUDY 4

Existing DEM comparison study

A: Portage area NED and IFSAR

NED: resolution 2 arcsec, Vertical Datum NGVD29, Horizontal Datum LL NAD 27; ultimately based on photogrammetric evaluations of aerial photographs acquired in the mid 20th century.
IFSAR DEM: acquired July 27 2001 (2004?), 10 m resolution, UTM6 WGS84, Vertical Datum MSL/EGM96. 'The flying height is 30,000 feet Above Mean Ground. The primary look direction is south. The secondary (alternate) look direction is east. Areas of missing data are interpolated using continuous curvature spline over non-data areas. Most incidences of non-data areas are due to radar shadow and layover due to steep terrain.'

To compare the two elevation data sets, they were both reprojected to UTM WGS84. An elevation difference map (IFSAR minus NED) was created after re-sampling both data sets to a common resolution of 30 meters.

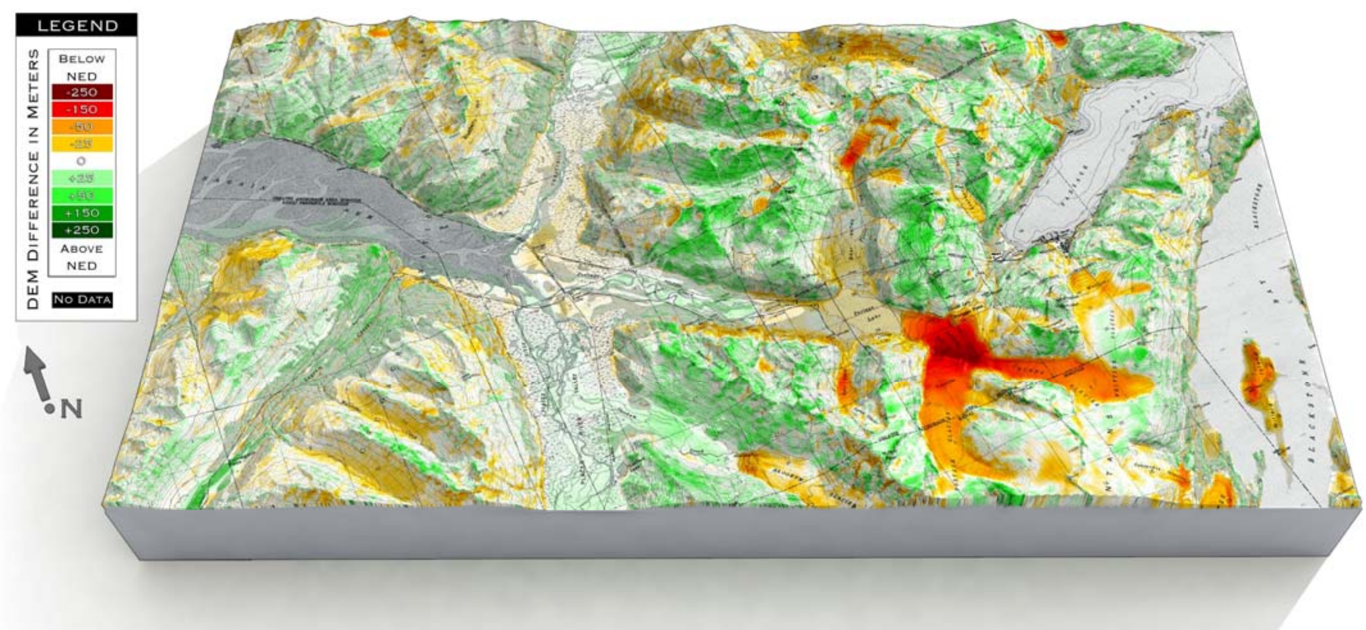
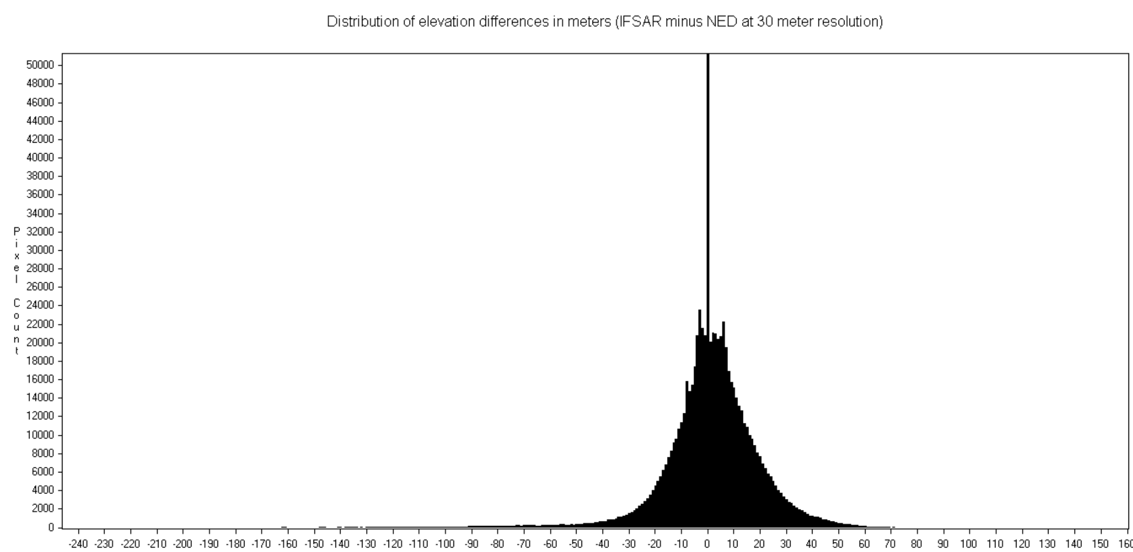


Figure : IFSAR minus NED difference map and topographic information.

Differences between IFSAR and NED:

- Mean difference: 1.02 meter (IFSAR > NED), standard deviation 22.16 meters; for non-glacier areas 3.37 meter mean difference, sd 13.94 m (see also histogram, figure).

- Glaciers (especially Portage Glacier, Burns, Byron & Billings Glaciers) reflecting real changes up to -245 m between NED / USGS 15 min DEM source image acquisition (1966-1974, or 1950?) and IFSAR-acquisition 2001, (shrinking as well as some growing, e.g. glacier on south flank of Maynard Mountain / N of Portage Glacier with IFSAR 20-70 m > NED, some accumulation areas higher in IFSAR).
- IFSAR-artifacts: Missing Willard Island; Passage Canal (& Blackstone Bay) coast cutoff / straightening (but also NED errors here); false peak (161 m > NED) at UTM6 402277 E, 6748218 N (spike?), layover interpolation e.g. at UTM 401078.9E, 6731632.2N (IFSAR 130 m > NED).
- NED-artifacts: Peak at 399952.2E, 6736432.2N cut away by seam stitching between D5 and C5.
- Sharp ridges up to 100 m higher in IFSAR (rounded down in NED), AK DRG map contours usually between IFSAR and NED values, often closer to the NED, e.g. 405196.9E, 6736062.2N: IFSAR 93 m > NED & Quadrangle Map, but sharp ridge visible in Ikonos imagery as in IFSAR.
- Some large differences on steep slopes (air photo shadow or radar shadow and layover interpolation results?), air photo shadow based NED errors likely on north-east facing slope south of Portage Creek.
- Vegetation & manmade structures surface in IFSAR (DSM instead of DEM), wooded areas generally higher than in bare-earth NED DEM.
- Generally much more detail in IFSAR, NED much smoother.



B: Skagway-Haines Area NED and SRTM

SRTM (Shuttle Radar Topography Mission) data are available for Alaska south of 60°N. The SRTM mission was flown in February 2000, acquiring both C-band and X-band data. The C-band data were processed into DEMs with 1 arc second resolution (about 30 meters in the North-South-direction). The SRTM DEMs contain voids especially in mountainous areas due to radar shadow, layover etc. (Dowding et al. 2004).

For the area around the Chilkoot and Taiya Inlets in South-East Alaska, 1 arc second resolution SRTM data and 2 arc second NED data were downloaded from the USGS Seamless Server. The SRTM data contained many small and big voids, mainly on south-facing slopes. For the valid data area, a difference map (SRTM minus NED) was created using 20 meter pixels.

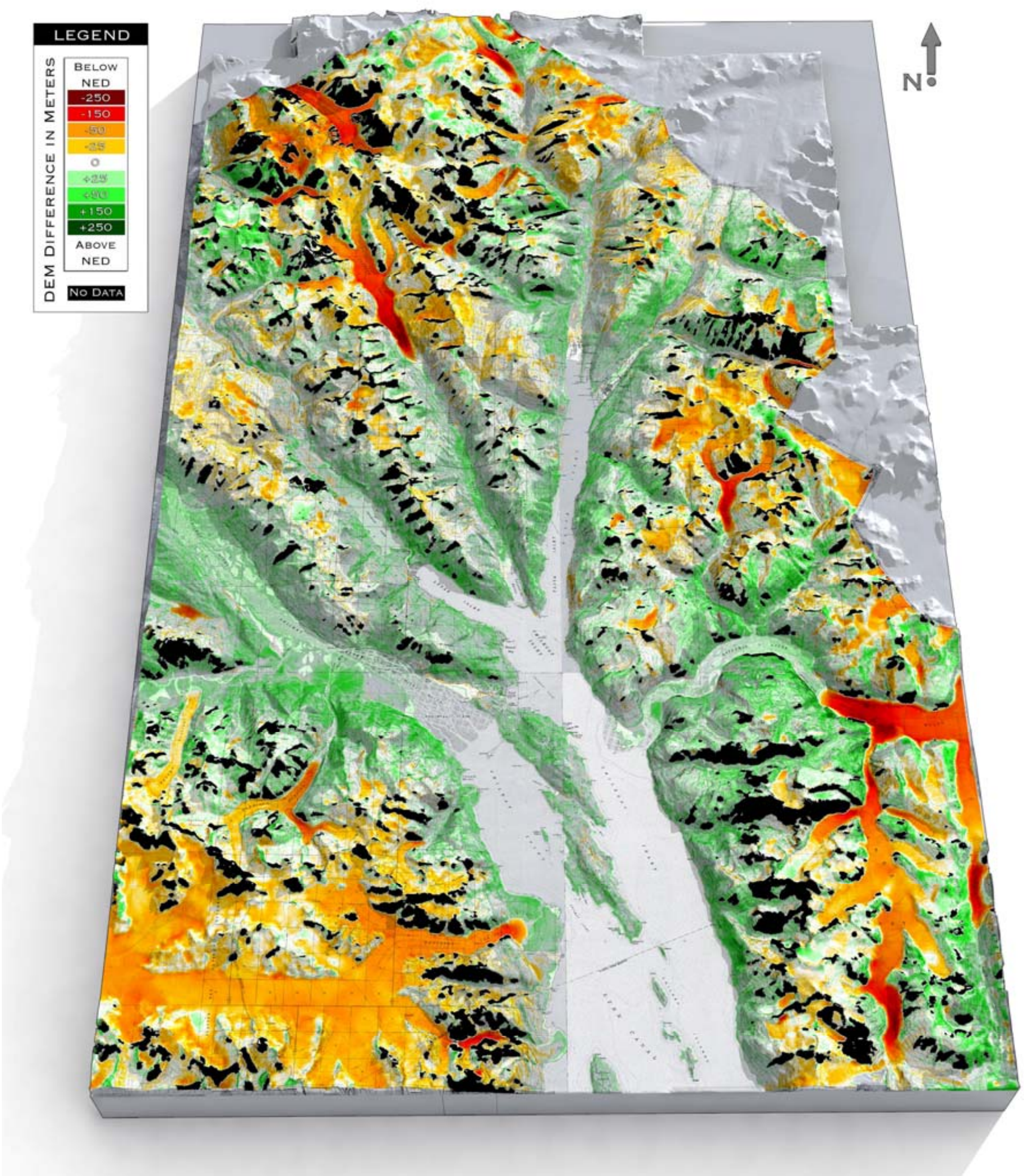
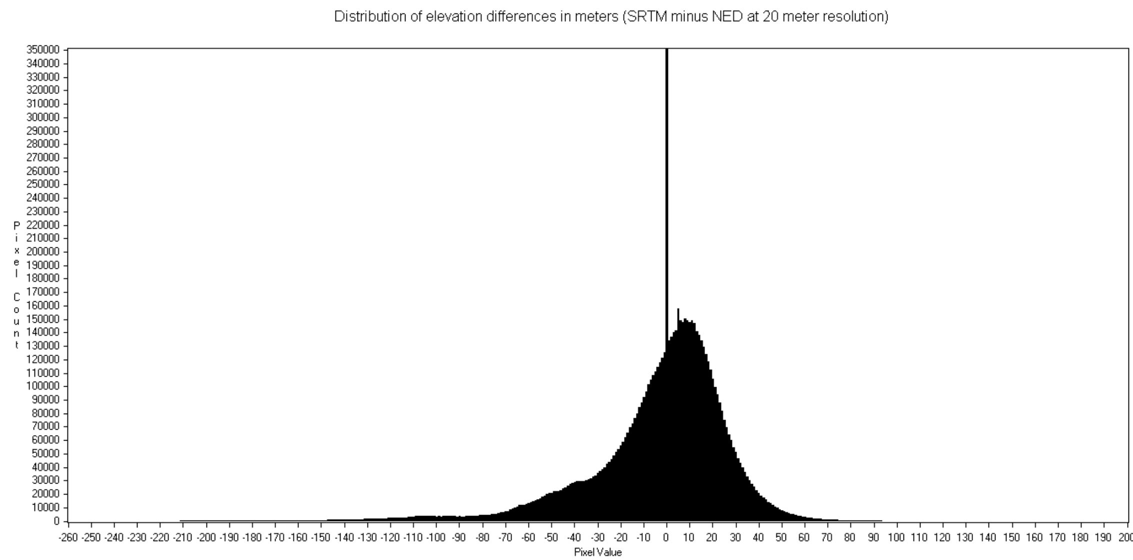


Figure : SRTM minus NED.



The basic differences are similar to the IFSAR versus NED comparison in the Portage area. The NED of this area is also based on many decades old aerial photographs, so that glacier surfaces are outdated, many glacier tongues having since receded by considerable amounts. SRTM elevations have a positive bias in areas of evergreen forest, where the surface measured is somewhere in the canopy instead of on the ground (see also Gesch 2005). Ridgelines are often lower in the NED than in the SRTM data.

References

1. Toutin, T., Chenier, R. (2002): GCP Requirement for High-Resolution Satellite Mapping.
2. Putman, W., Worum, G., Lee, M. (2005): Final Report, NASA Grant NAG 13-01010, Vegetation and Community Mapping of the Tanana Valley with Applications for Public Safety, Natural Hazards Management, and Fire Protection, December 2005.
3. Putman, W. (2004): High-Resolution Satellite Image Processing in Interior Alaska, The Good, the Bad, and the Ugly, Tanana Chiefs Conference, Fairbanks, AK, January, 22, 2004.
4. Dennis, M., Kennedy, M., Philbrook, M., Dowling, J., McMahon, R. (2006): Alaska GIS- North to NaD 83, Anchorage, AK, GIS Jam, Alaska Surveying and Mapping Conference, February, 2006.
5. Cheng, P., Toutin, T., Zhang, Y., & Wood, M. (2003): Quickbird – Geometric Correction, Path and Block Processing and Data Fusion. EOM www.pcigeomatics.com/services/support_center/tech_papers/eom_Quickbird.pdf.
6. PCI Geomatics (2007): Geomatica Version 10.1 Help.
7. Toutin, T. & Cheng, P. (2002): Quickbird – A Milestone for High-Resolution Mapping. Earth Observation Magazine April 2002.

Cheng, P., Toutin, T., Zhang, Y. & Wood, M. (2003): Quickbird – Geometric Correction, Path and Block Processing and Data Fusion. EOM www.pcigeomatics.com/services/support_center/tech_papers/eom_Quickbird.pdf.

Dennis, M., Kennedy, M., Philbrook, M., Dowling, J., McMahon, R. (2006): Alaska GIS-North to NaD 83, Anchorage, AK, GIS Jam, Alaska Surveying and Mapping Conference, February, 2006.

Dowding, S., Kuuskivi, T. & Li, X. (2004): Void fill of SRTM elevation data – principles, processes and performance. *ASPRS Images to Decision: Remote Sensing Foundation for GIS Applications, September 12-16, 2004, Kansas City, Missouri. (Intermap White Paper).*

Gesch, D. (2005): Vertical Accuracy of SRTM Data of the United States: Implications for Topographic Change Detection. *Presentation at SRTM Data Validation and Applications Workshop, June 14, 2005.*

Jacobsen, K. (2001): Automatic matching and generation of orthophotos from airborne and spaceborne line scanner images. *Proc. Joint ISPRS Workshop "High Resolution Mapping from Space 2001", University of Hannover, Germany.*

Jacobsen, K. (2007): Mapping from Space http://cors-tr.iku.edu.tr/Konecny/2007_jac_MapRio3.pdf.

Mercer, J.B., Allan, J., Glass, N., Rasmussen, J. & Wollerheim, M. (2003): Orthorectification of satellite imagers using external DEMs from IFSAR. – *Proc. Joint*

ISPRS Workshop "High Resolution Mapping from Space 2003", Hannover, Germany, October 6-8th, 2003.

Passini, R.M. & Jacobsen, K. (2004): Accuracy of digital orthophotography from high resolution space images.

PCI Geomatics (2007): Geomatica Version 10.1 Help.

Putman, W. (January, 22, 2004): High-Resolution Satellite Image Processing in Interior Alaska, The Good, the Bad, and the Ugly, Tanana Chiefs Conference, Fairbanks, AK.

Putman, W., Worum, G., Lee, M. (December 2005): Final Report, NASA Grant NAG 13-01010, Vegetation and Community Mapping of the Tanana Valley with Applications for Public Safety, Natural Hazards Management, and Fire Protection, December 2005.

Toutin, T., Chenier, R. (2002): GCP Requirement for High-Resolution Satellite Mapping.

Toutin, T. & Cheng, P. (2002): Quickbird – A Milestone for High-Resolution Mapping. Earth Observation Magazine April 2002.