THE ABSOLUTE AND RELATIVE GEOLOCATION ACCURACIES OF QB02 AND WV01

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ABSTRACT

DigitalGlobe's commercial imaging constellation contains two high resolution satellites: QuickBird-2 (QB02), launched in October 2001, and WorldView-1 (WV01), launched in September 2007. The absolute and relative geolocation accuracies of both these satellites change over time. To ensure that all DigitalGlobe satellite imagery consistently meets the accuracy requirements of typical customers, the geolocation accuracies of both satellites are assessed twice a month. The results are binned into monthly and quarterly geolocation statistics which either confirm compliance or motivate corrective action. The last two years of quarterly QB02 geolocation statistics ending in November 2008 are presented. All quarterly WV01 statistics accumulated since launch to November 2008 are also presented. If the absolute geolocation accuracy of an image strip is represented by the average geolocation error projected to nadir, then the quarterly 90th percentile of QB02 absolute accuracy fluctuates between 14 to 21 meters, while the quarterly 90th percentile of WV01 varies from 4.0 to 5.3 meters. If the relative geolocation accuracy of an image strip is represented by the largest observed change in absolute, nadir projected error, then the highest, quarterly relative error of QB02 fluctuates randomly between 12 and 24 meters, while the highest, quarterly relative error of WV01 has never exceeded 4.8 meters and has steadily decreased to 1.8 meters as of November 2008.

INTRODUCTION

DigitalGlobe is a commercial imagery and information company founded in 1992 that maintains a constellation of imaging platforms. In addition to a global network of aerial imagery providers, DigitalGlobe operates two high resolution imaging satellites: QuickBird-2 (QB02), and WorldView-1 (WV01).

QB02 was launched in October 1997. Typical operating altitude is approximately 450 km. The swath width is approximately 16.9 km at nadir. QB02 has 5 imaging bands: four multispectral bands (blue, green, red, near-infrared) and a panchromatic band. The PAN band has a 0.61 meter GSD at nadir. This is four times smaller than the 2.4 meter GSD of the four MS bands, which make ground features far more recognizable. Thus, PAN is the band used to assess the absolute geolocation accuracy for QB02.

WV01 was launched in September 2007. Typical operating altitude is approximately 496 km. The swath width is approximately 17.7 km at nadir. WV01 is a PAN only satellite, and it possesses a 0.50 meter GSD at nadir.

In order to monitor the health of both satellites on orbit, and to verify the intact functioning of their common image production system on the ground, the absolute geolocation accuracy of imagery products are checked twice a month. Accuracy statistics compiled from the bi-monthly sampling are used to compare each satellite's performance against expectations. If any deviation is found, corrective steps are taken within the production system to bring accuracy back into specification. The most common correction is reprocessing the attitude data, which can be performed as often as once a month for WV01. Other improvements to geolocation accuracy are required less often, but have included recalculating ephemeris, compensating for a leap second, and refining parameters in the camera model.

METHODS

Ground Control Points

Ground control points are used to measure the geolocation accuracy of QB02 and WV01 imagery. The same suite of 30 ground control point collections (called "geocal sites", short for "geometric calibration sites") are used to analyze the image strips from both satellites, creating a satellite independent methodology. The geocal sites are listed in Table 1. All gcps are surveyed to sub-meter accuracy, and most have 25 cm accuracy. While DigitalGlobe owns an enormous database of gcps collected by professional surveyors, these particular gcp sets were chosen to achieve thorough latitude coverage of about 2 geocal sites every 10 degrees of latitude. Latitude coverage is important because it presents both of the satellites and their common production system with a nearly complete set of possible input parameters. Longitude of the geocal sites was ignored, since the staggered orbits of the satellites eventually bring all longitudes into view. Geolocation analysis is performed upon all images of geocal sites whose off nadir angle lies between 0° to 30° and whose cloud cover is 50% or less. Due to differences in agility and revenue demands, QB02 typically collects about 20 geocal strips in a month, while WV01 can easily collect 50.

Absolute Geolocation Accuracy of an Image

To keep pace with collection, geocal strips for each satellite are catalogued and analyzed twice a month. The geocal strips are made into raw, calibration level products that do not incorporate complicating factors like digital terrain models. To calculate the geolocation error of a gcp, the image coordinates of that point, i.e. the line (row) and pixel (column) location of the gcp, must be determined and recorded. This task can be done manually, by a person comparing the imagery to a sketchbook for the gcps, or it can be done automatically by computer, with image recognition routines comparing the imagery to small reference images collected in advance. Both human and computer marking methods are good to 1 line/pixel. Marking gcps accurately and reproducibly is very important, because even small mistakes, i.e. fractional lines/pixels, add a little geolocation error.

The image coordinates for each gcp are projected to the ground using the rigorous camera model for the appropriate satellite. The projected gcp location inevitably differs from the surveyed coordinates of the gcp, see Figure 1. The difference is the absolute geolocation error of that gcp, a vector quantity that points from the projected location (also called the measured location, meaning "measured in the image") to the true location. This vector

geocal site	gcps	mean geodetic latitude
Fairbanks, Alaska, USA	16	64.843751
Reykjavik, Iceland	8	64.117733
Anchorage, Alaska	15	61.314978
Hamburg, Germany	11	53.597883
Calgary, Alberta, Canada	10	51.034162
Boise, Idaho	14	43.585712
Rome, Italy	10	41.907479
Morrison, Colorado, USA	19	39.708905
Castle Rock, Colorado, USA	50	39.493607
Fresno, California, USA	57	36.786116
Las Vegas, Nevada, USA	39	36.196316
Phoenix, Arizona, USA	104	33.489236
El Paso, Texas, USA	19	31.773743
Tabuk, Saudi Arabia	10	28.398953
Abu Dhabi, United Arab Emirates	15	24.442636
Chiang Rai, Thailand	18	19.861685
Salalah, Oman	35	17.044803
Georgetown, Guyana	9	6.797929
Paramaribo, Suriname	14	5.811408
Djakarta, Indonesia	10	-6.196819
Luanda, Angola, Africa	7	-8.810014
Sao Raimundo Monato, Brazil	14	-8.992744
Lima, Peru	39	-12.085513
Townsville, Australia	19	-19.29315
Port Hedland, Australia	28	-20.380412
Rio de Janeiro, Brazil	18	-22.839594
Perth, Australia	66	-32.097607
Corral De Bustos, Argentina	15	-33.260725
Adelaide, Australia	42	-34.925389
Dunedin, New Zealand	10	-45.882378

Table 1. Ground control point collections, or geocal sites, used in the analysis of DigitalGlobe satellite imagery. The sites are distributed such that there are about 2 geocal sites every 10 degrees of latitude.

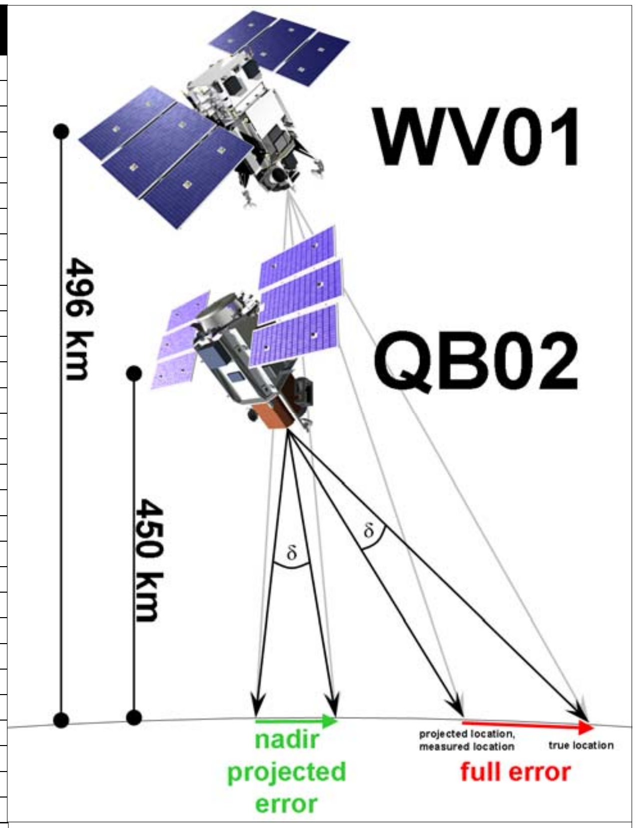

Figure 1. "Full" geolocation error is found by projecting the image of a gcp to the ground, then comparing to the surveyed location. The "nadir projected" geolocation error is found by multiplying the subtended angle **δ** by the altitude of the satellite.

incorporates all aspects of the collection like off nadir angle, hence it is called the "full geolocation error." Full error is probably the most familiar measure of accuracy, and is most meaningful to end users of imagery products, e.g. those curious about how much error to expect in a finished, orthorectified product.

The full error of a gcp can also be scaled back to nadir, creating the angular equivalent but somewhat shorter "nadir projected error," see Figure 1. This is done by finding the small angle subtended by the full error (on the order of microradians, **δ** in Figure 1), then multiplying by the altitude of the relevant satellite. Nadir projected error may be unfamiliar to most, but it is quite useful when tracking the health of the satellite itself, especially to those who appraise the attitude determination subsystem. In other words, nadir projection estimates the amount of geolocation error inherent in the satellite's hardware, before being magnified even further by off nadir angle. Nadir projection also helps make comparisons of different data sets more meaningful, since data from different months or quarters would certainly have a different nadir angle distribution.

Whichever error is used, the error vectors can be collected into a quiver plot like Figures 2a and 3a. The final step is to summarize the absolute accuracy of an entire geocal strip. This investigation uses the average geolocation error of the strip. Figures 2b and 3b show the average geolocation errors of the quiver plots shown in 2a and 3a respectively. This average error is also a vector, but the magnitude is generally discussed because the direction is unimportant to most customers.

Relative Geolocation Accuracy of an Image

Further analysis examines how the absolute geolocation errors change within an image. These changes can be quantified by systematically calculating the vector differences between all pairs of absolute errors in the image. For N absolute errors, combinatorics reveals there are N(N-1)/2 unique pairs. Relative errors can be computed using both full errors and nadir projected errors.

Relative error is so undesirable to certain customers that the worst relative error in a strip is sometimes used to convey the quality of that strip. In accordance with this practice, the worst relative error has been used to represent the relative geolocation accuracy of a strip in this investigation. The worst relative error is also a vector, but again the magnitude is far more important than the direction. Figures 2c and 3c show the worst relative errors for the strips featured in Figures 2a and 3a respectively, and also the two absolute errors that created them.

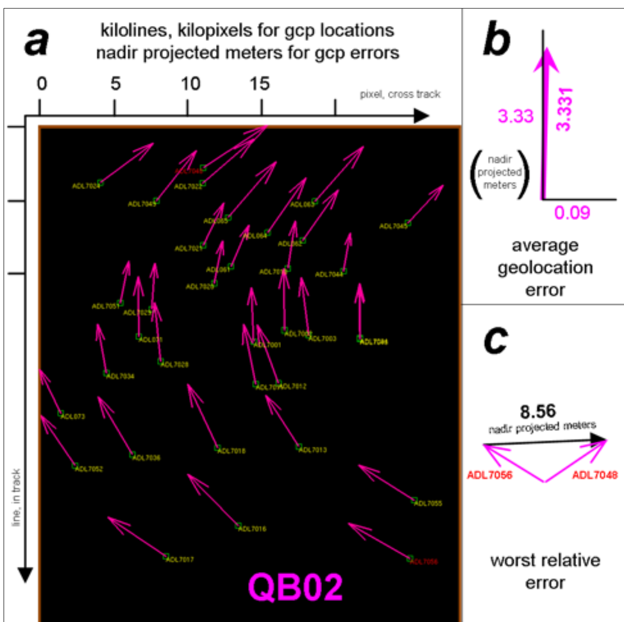

Figure 2. (a) sample quiver plot for QB02 using nadir projected errors. **(b)** the average geolocation error, the magnitude of which is the measure of absolute geolocation accuracy. **(c)** worst relative error, the magnitude of which is the measure of relative geolocation accuracy. The two gcps that created the worst relative error are also highlighted in red font inside Figure 2a.

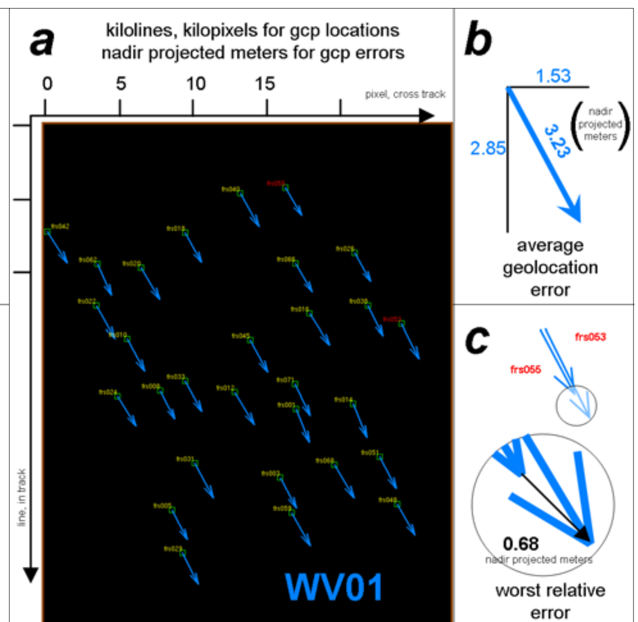

Figure 3. (a) sample quiver plot for WV01 using nadir projected errors. **(b)** the average geolocation error, the magnitude of which is the measure of absolute geolocation accuracy. **(c)** worst relative error, the magnitude of which is the measure of relative geolocation accuracy. The two gcps that created the worst relative error are also highlighted in red font inside Figure 3a.

Absolute Geolocation Accuracy of a Satellite

The absolute geolocation accuracy of each satellite is deduced by statistically analyzing the absolute geolocation accuracies of geocal strips over time. The absolute geolocation accuracy of each geocal strip is plotted against acquisition time to create Figures 4 and 5. The points represent the magnitudes of the nadir projected errors; for simplicity, points for the full error magnitudes have been omitted.

Performance metrics are initially constructed using monthly subsets of the strips. Bin edges are placed at midnight on the first of every month, a technique that sidesteps irregular month length. The monthly statistics are too numerous to present in this paper; these are omitted in favor of quarterly statistics, which are created by combining the following months into the following quarters: Jan, Feb, and Mar become the first quarter (1Q), Apr, May, Jun become the second quarter (2Q), and so on. The large number of points in a quarter makes the quarterly statistics much less volatile than the monthly ones, creating a more stable and balanced measure for the geolocation accuracy of each satellite.

Each quarter is evaluated by taking the 90^{th} percentile of the average geolocation error magnitudes. Figures 4 and 5 also show the satellite accuracies for each quarter as a large, centered symbol plotted at the height of the 90^{th} percentile. For clarity, the value of the 90^{th} percentile is also printed.

Because there are many different ways to take a percentile, the exact percentile formula used in this investigation should be discussed. Let N be the number of geolocation errors in a strip, and let the geolocation errors be labeled as e_1 to e_N. The left hand side of the equation

$$0.9*N + 0.5 = \text{integer} + \text{fraction}$$

is evaluated, and the result is split into an integer and a fraction as suggested by the right hand side. The 0.5 is added to the left hand side to create a more unbiased estimator of the 90^{th} percentile, a result determined with Monte Carlo trials using random numbers of known distribution. The integer and fraction are used to linearly interpolate between two of the N errors:

$$90^{th} \text{ percentile} = e_{\text{integer}} + \text{fraction}*(e_{(\text{interger}+1)} - e_{\text{integer}})$$

For example, if there were ten geolocation errors, the left hand side would evaluate to 9.5, which implies the 90^{th} percentile would be halfway between the ninth and tenth error.

Relative Geolocation Accuracy of a Satellite

Relative geolocation statistics are binned into quarters just like the absolute statistics. Figures 6 and 7 plot the magnitude of the worst relative error in each geocal strip as a single point. Similar to Figures 4 and 5, the points correspond to relative error magnitudes calculated using nadir projected errors, not full errors.

Because relative error is held in such negative regard by select customers, the relative geolocation accuracy of a satellite is represented by the maximum worst relative error in that quarter, i.e. the worst of the worst. This is an extremely strict and unforgiving measure of relative geolocation accuracy, but one that readily distinguishes QB02 from WV01. Figures 6 and 7 emphasize the maximum worst relative error for each satellite with an enlarged symbol. For clarity, the magnitude of the maximum worst relative error is also printed.

RESULTS

Absolute Geolocation Accuracy

The absolute geolocation accuracy of QB02 is fairly good given the dated attitude determination subsystem and long service life. QB02 has routinely achieved a nadir projected performance of about 20 meters over a quarter, but never improves below 14 meters, see Figure 4. Sampling has also been sporadic for QB02, since the low agility can restrict the number of available geocal strips to as few as ~50 per quarter.

On the other hand, the absolute geolocation accuracy of WV01 is outstanding, see Figure 5. The high agility of WV01 has provided so many geocal strips per quarter, sampling has never been a concern. Since launch, the nadir projected quarterly performance has never exceeded 5.5 meters, with typical performance in the 4 meter range. In particular, the good accuracy in 4Q2008 has reversed a slight upward trend, returning the performance to levels seen immediately after launch.

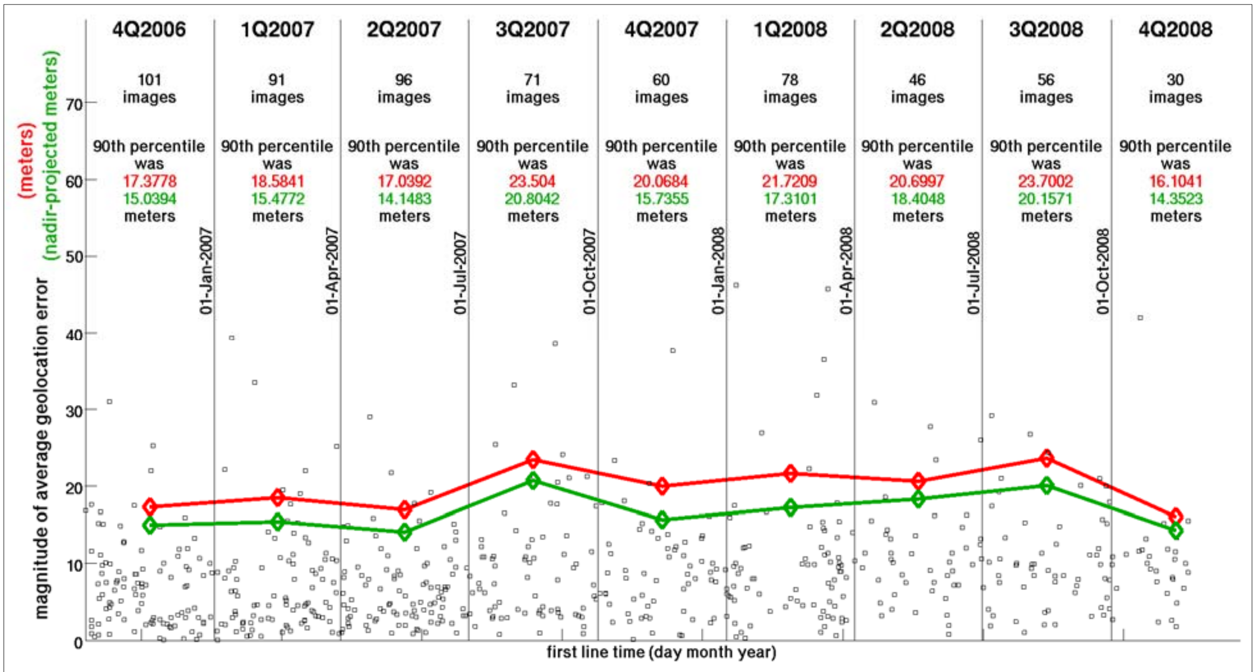

Figure 4. Absolute geolocation accuracy of QB02 compiled into quarterly bins. The square points are the magnitudes of each geocal strip's average geolocation error when using nadir projected errors. Point markers for the corresponding full errors are omitted for clarity. The red line is the quarterly 90th percentile of the average full errors, while the green line is the quarterly 90th percentile of the average nadir projected errors.

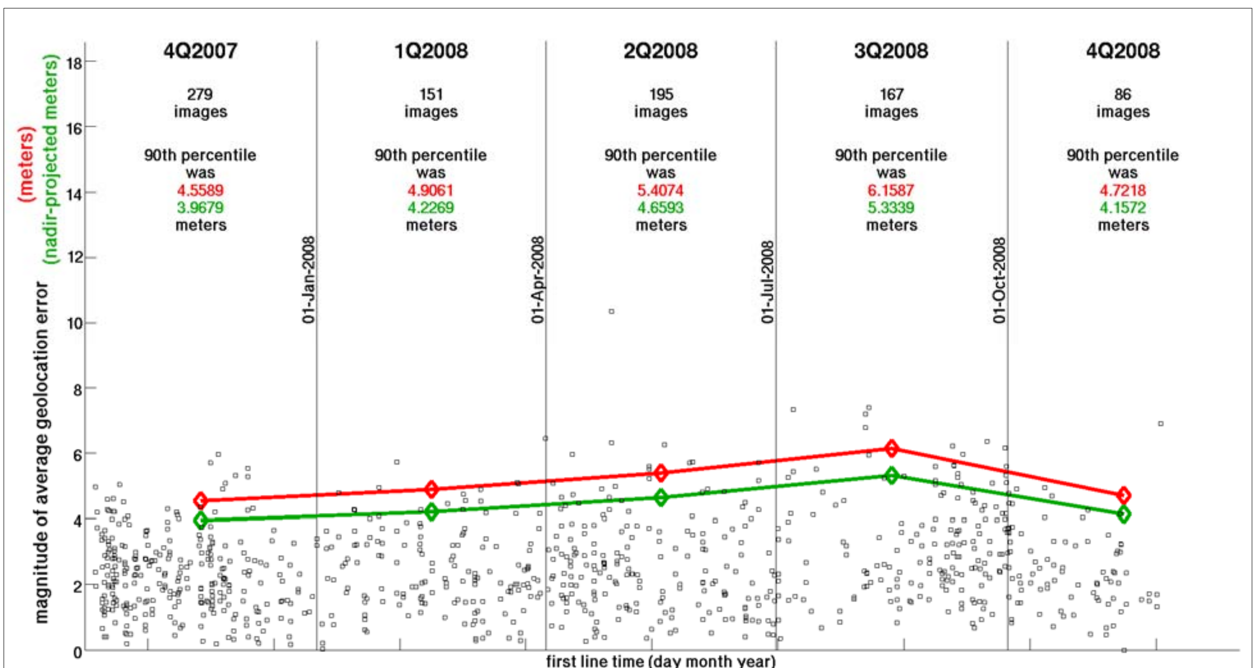

Figure 5. Absolute geolocation accuracy of WV01 compiled into quarterly bins. The square points are the magnitudes of each geocal strip's average geolocation error when using nadir projected errors. Point markers for the corresponding full errors are omitted for clarity. The red line is the quarterly 90th percentile of the average full errors, while the green line is the quarterly 90th percentile of the average nadir projected errors.

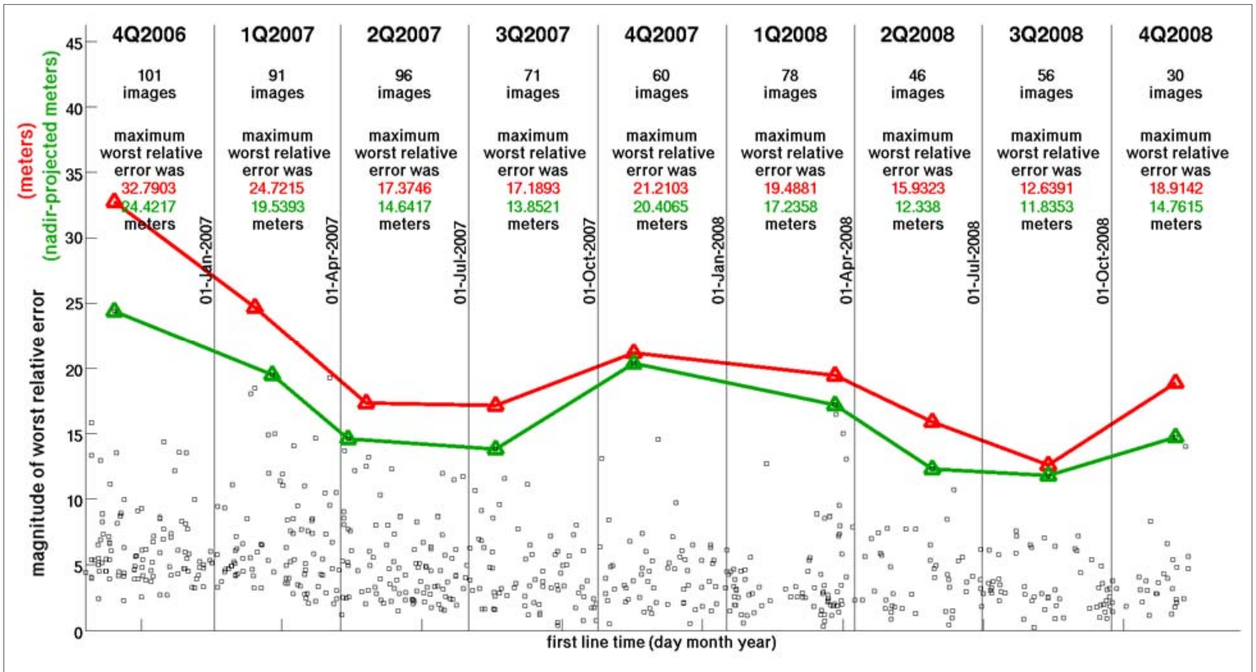

Figure 6. Relative geolocation accuracy of QB02 compiled using quarterly bins. The square points are the magnitudes of each geocal strip's worst relative error when nadir projected errors are used. Point markers for the corresponding full errors are omitted for clarity. The red line is the maximum of the full worst relative errors, while the green line is the maximum of the nadir projected worst relative errors. The maximum worst relative error in the nadir projected and full data sets are usually in the same geocal strip, but not always.

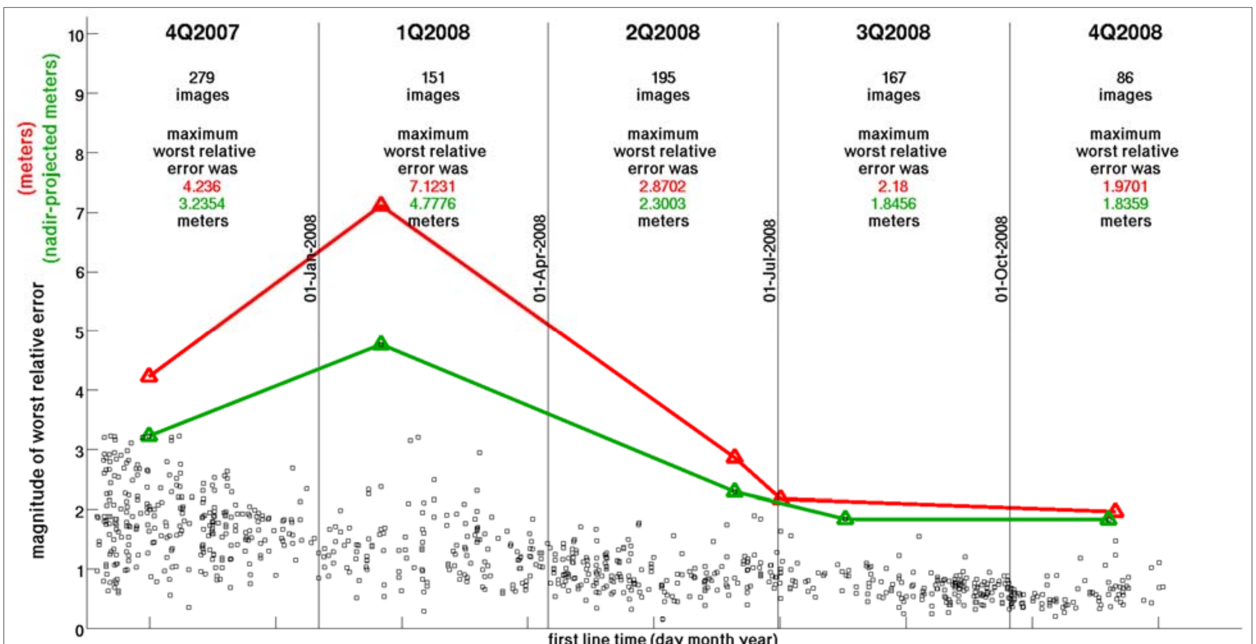

Figure 7. Relative geolocation accuracy of WV01 compiled using quarterly bins. The square points are the magnitudes of each geocal strip's worst relative error when nadir projected errors are used. Point markers for the corresponding full errors are omitted for clarity. The red line is the maximum of the full worst relative errors, while the green line is the maximum of the nadir projected worst relative errors. The maximum worst relative error in the nadir projected and full data sets are usually in the same geocal strip, but not always.

Thus, WV01 outperforms QB02, sometimes by a factor of three. The absolute accuracy curves of both satellites are directly compared in Figure 8a. To avoid complicating effects like differences in the off nadir angle distribution, the nadir projected statistics are compared. WV01 is superior because the attitude determination subsystem, containing star trackers, gyroscopes, etc, performs better.

Relative Geolocation Accuracy

The relative geolocation accuracy of QB02 is less than ideal, and has also been very challenging to improve. When a quiver plot has a swirl or whorl pattern like Figure 2a, the worst relative error immediately becomes large, perhaps twice the average geolocation error or beyond. These cowlick patterns occur when components of error continually grow or shrink as the line count advances. Figure 6 shows how regularly this occurs for QB02. Using the nadir projected statistics, no quarter has a maximum worst relative error below ~12 meters, and some are as high as 20 meters. High relative error like this is also called “shear” by some customers, perhaps because the pattern of quiver plot arrows is reminiscent of fluid flow. Imagery with shear can be difficult to use in some applications because it requires many ground control points to correct.

Looking to the nadir projected statistics in Figure 7, the worst quarter of relative accuracy for WV01 was just 4.8 meters. WV01’s relative geolocation accuracy has actually improved post launch, and has stabilized near 1.8 meters in 4Q2008. Imagery with this little shear is very easy to use, such that some customers can use it directly without using any gcps at all.

WV01 outperforms QB02 in relative geolocation accuracy for the same reason as before: it possesses a better attitude determination subsystem. This is readily seen in Figures 3a and 3c; the quiver plot has practically no shear compared to Figure 2a and 2c. Figure 8b also makes this very apparent, especially in recent quarters like 3Q2008 where WV01 relative accuracy can be nearly six times better than QB02. Since 4Q2007, the biggest quarterly worst relative error from WV01 has only been 4.8 meters, which is well below the best quarterly relative error for QB02 at 11.8 meters.

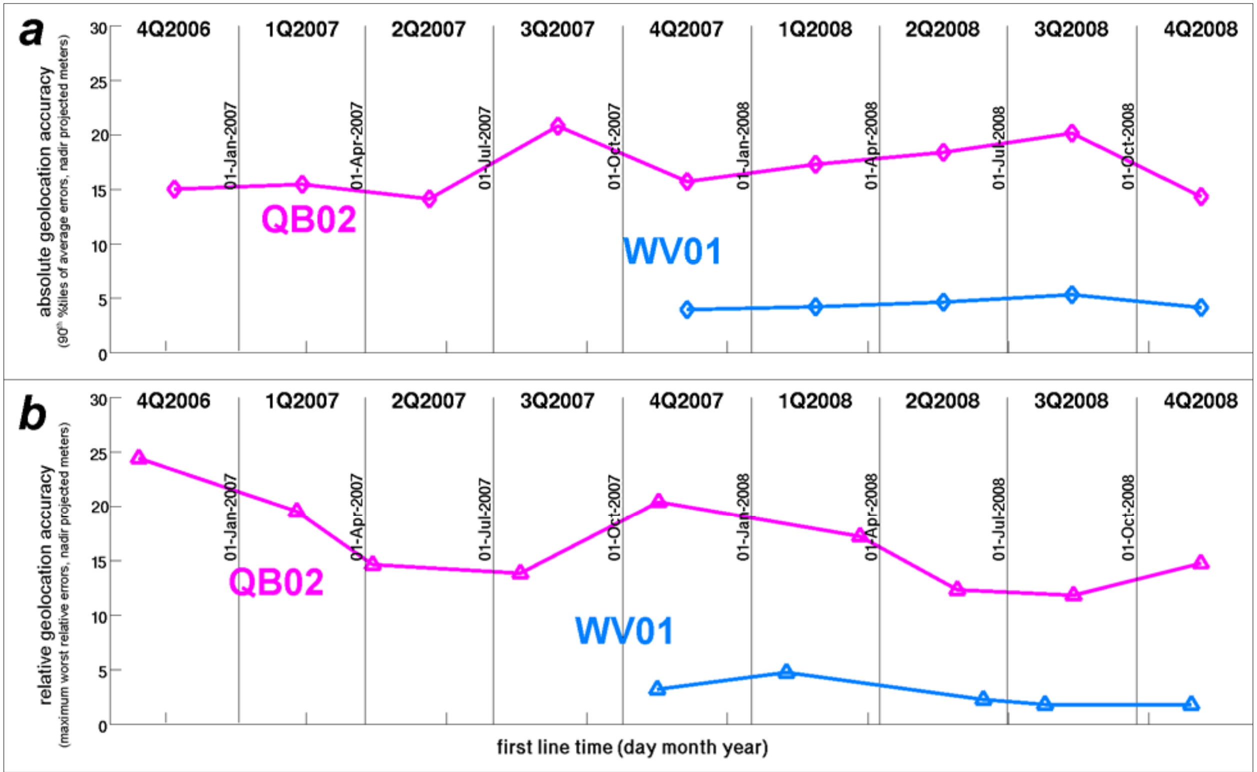

Figure 8. (a) Absolute geolocation accuracy of QB02 versus WV01. The nadir projected performance curves of Figures 4 and 5 are plotted here with the same vertical and horizontal scaling. WV01 always outperforms QB02 by a factor of three, and sometimes more. **(b)** Relative geolocation accuracy of QB02 versus WV01. The nadir projected performance curves of Figures 6 and 7 are plotted here on the same scale. Note the worst quarter of WV01 is far better than the best quarter of QB02.

CONCLUSIONS

When using nadir projected statistics compiled into quarterly bins from 4Q2006 until 4Q2008, QB02 has an absolute geolocation accuracy between 14 and 21 meters. While quarterly WV01 absolute geolocation statistics only go back to 4Q2007, they are far better, always between 4.0 to 5.3 meters. Relative geolocation accuracy for WV01 is better as well, with quarterly performance between 1.8 to 4.8 meters, as compared to 12 to 24 meters for QB02.

Both the absolute and relative geolocation accuracies of each satellite are primarily determined by the attitude determination subsystem. WV01 has outperformed QB02 because the attitude determination subsystem performs better during routine operation. Other contributors to absolute and relative geolocation error, such as errors in the ephemeris, time tagged line count, and the camera model, are small and constant, rarely needing adjustment or correction outside the initialization period immediately following launch.

In the future, DigitalGlobe will launch a third satellite, WorldView-2 (WV02). WV02 will have a PAN band similar to WV01 with a 0.46 meter GSD, and also 8 multispectral bands that all have a 1.84 meter GSD. The absolute geolocation accuracy of WV02 is expected to be a scaled version of WV01, meaning about the same angular error but scaled to the appropriate altitude.