THE MONOSCOPIC AND STEREOSCOPIC GEOLOCATION ACCURACY OF THE DIGITALGLOBE SATELLITE CONSTELLATION

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ABSTRACT

The geolocation accuracy of DigitalGlobe's satellite constellation has been monitored over the last 2 years. Using quarterly statistics compiled from the analysis of monoscopic images, the horizontal geolocation accuracy of each satellite was shown to be stable over time. QuickBird-2 always had a quarterly 90^{th} percentile between 13 and 18 meters projected to nadir over the last two years. WorldView-1 accuracy varied between 3.6 to 4.9 meters at nadir over the same 2 year period. Throughout 2010, WorldView-2 monoscopic accuracy fluctuated between 2.4 and 3.5 meters at nadir.

In addition, WorldView-2 stereo pairs have been examined using similar methods. Quarterly statistics reveal stable accuracies in both the horizontal and vertical components of stereoscopic geolocation error. During 2010, the CE90 of horizontal error ranged between 2.6 and 4.6 meters, while the LE90 of vertical error was between 3.1 to 4.5 meters.

KEYWORDS: DigitalGlobe, geolocation, geoposition, accuracy, stereo

INTRODUCTION

DigitalGlobe possesses a constellation of three high resolution imaging satellites: QuickBird-2 (QB02), launched in 1997; WorldView-1 (WV01), launched in 2007; WorldView-2 (WV02), launched in 2009. At this writing, the altitude of QB02 [WV01] {WV02} is approximately 450 [496] {770} kilometers. Each satellite has a panchromatic band of sub-meter resolution: QB02 [WV01] {WV02} has a 0.61 [0.50] {0.46} meter GSD at nadir. QB02 {WV02} also has 4 {8} additional multispectral bands, all with a GSD of 2.44 {1.85} meters at nadir. The swath width of QB02 [WV01] {WV02} imagery is 16.8 [17.7] {16.4} kilometers at nadir.

It is vital that the geodetic locations of imaged pixels from all spectral bands are properly reconstructed after collection, so that imagery products of useful quality can be sold to the public. Since all three satellites have a panchromatic band, checking the geolocation accuracy of panchromatic imagery is a convenient, uniform method of assessing the quality of the entire constellation. Note that all spectral bands aboard a satellite have the same geolocation accuracy; the panchromatic band is favored because the higher resolution facilitates the recognition of ground control points.

METHODS

Ground Control Points

A collection of 27 geometric calibration (geocal) sites have been used to assess the monoscopic and stereoscopic geolocation accuracy of all imagery, see Table 1. Each geocal site has approximately 10 to 100 ground control points (GCPs) surveyed to submeter accuracy in both the horizontal and vertical directions. The set of geocal sites was chosen to extend across all latitudes with land. Because the ingredients to geolocation, e.g. attitude and ephemeris, change along the descending orbit with latitude, this confirms that good geolocation can be constructed for all images. Longitude of the geocal sites was largely ignored, since the Earth's rotation brings many longitudes into view on a given day. There was one exception: geocal sites of similar latitude had widely separated longitudes to provide redundancy against cloud cover.

Geolocation Assessment of Monoscopic Images

To perform a monoscopic geolocation analysis of each satellite, all suitable images acquired in a quarter were found with database searches. Only images between 0 to 32° off nadir and containing at least 2 GCPs were used. The monthly collection totals for QB02 [WV01] {WV02} rarely exceeded 30 [50] {50} geocal images, so the quarterly totals were no more than triple these values. After discovery, the images were ordered as raw, non-orthorectified products. All GCPs within the images were marked using an ENVI based viewer. Care was taken to mark all GCPs to within 1 line/pixel. Automated matching methods to mark GCPs were tried, but human oversight was usually required to remark, or totally remove, outliers.

Once all GCPs in an image were marked, the relevant panchromatic camera model was used to project the marked pixel to the same height above the ellipsoid as the GCP. Thus, the monoscopic geolocation error was forced to be purely horizontal as seen by an observer on the ground. Figure 1 shows how the projected pixel missed the affiliated GCP, as expected. A vector that pointed from the projected location to the true coordinates represents the "full" geolocation error of that GCP; this was also the magnitude of the error seen by a local observer.

In addition, one can express geolocation error as a "nadir projected" equivalent. If the small angle between the projected and truth view vectors (**δ** in Figure 1) was multiplied by the appropriate altitude, a somewhat smaller "nadir projected" error was found. This represents what the full error would have been if the image had been taken at nadir. While unfamiliar to most, nadir projection provided an easy way to compare geolocation error in a variety of images taken at different off nadir angles, and also between different satellites.

After all geolocation errors for an image had been computed, they were averaged as vectors to produce a mean geolocation error. The nadir projected and full errors had different averages, and were handled separately. The magnitude of the appropriate average error was used to represent the image in performance statistics. Quarterly performance metrics were favored over monthly ones because the larger number of points suppresses volatility.

The 90th percentile of average geolocation errors in a quarter was the monoscopic performance metric for a satellite. It was called the "CCAP metric," after the NGA Image Quality and Utility Program / Civil and Commercial Applications Project (NIQU/CCAP) which used the same metric to assess DigitalGlobe geolocation

geocal site	# of GCPs	latitude
Fairbanks	23	64.85°
Reykjavik	8	64.12°
Anchorage	14	61.31°
Hamburg	11	53.60°
Calgary	9	51.03°
Boise	14	43.56°
Rome	8	41.90°
Sevilla	10	37.40°
Las Vegas	48	36.17°
Phoenix	92	33.49°
Tabuk	9	28.41°
Abu Dhabi	11	24.45°
Acapulco	8	16.85°
Al Mukalla	10	14.54°
Georgetown	9	6.80°
Suriname	11	5.80°
Jakarta	10	-6.20°
Souza	12	-6.73°
Sao Raimundo Monato	13	-8.99°
Oshakati	13	-17.78°
Townsville	18	-19.29°
Rio	23	-22.81°
Brisbane	13	-27.47°
Perth	58	-32.10°
Ministro Pistarini	20	-34.82°
Melbourne	22	-37.92°
Dunedin	8	-45.88°

Table 1. Geometric calibration sites used to assess the geolocation accuracy of DigitalGlobe imagery. Every image included in official statistics had at least 2 gcps.

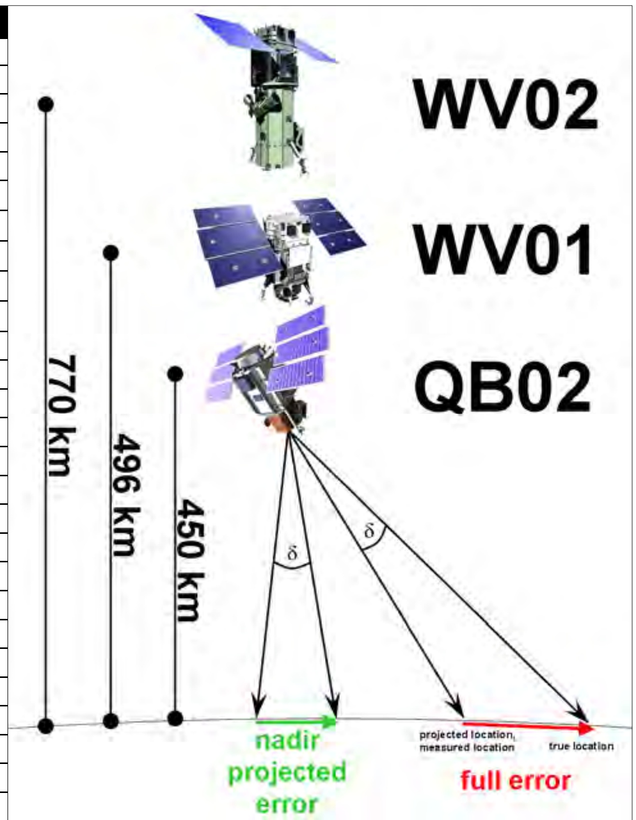

Figure 1. Monoscopic geolocation error can be expressed as two different vectors: "full" error, and a "nadir projected" error of the same interior angle (**δ**).

accuracy. Because there are many different ways to take a percentile, it is essential to discuss the exact formula. Let N be the number of average geolocation errors in a quarter, 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 indicated by the right hand side. The 0.5 is added to the left hand side to unbias the estimate of the 90^{th} percentile. The integer and fraction are used to linearly interpolate between two of the N errors:

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

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

Geolocation Assessment of Stereo Pairs

The geolocation accuracy of WV02 stereo pairs has also been studied using similar methods. Each quarter, database searches located stereo pairs that satisfied three criteria: both acquisitions in the stereo were less than 32° off nadir, the stereo convergence angle was between 40° to 50° (see Figure 2), and at least two GCPs were common to both collects. The same GCPs used in the monoscopic study were also used to assess WV02 stereo pairs, without restriction. WV02 collected no more than 20 stereos a month over geocal sites, or no more than 60 in a quarter.

For stereos, only GCPs present in both collects can be used, which tends to reduce the number of GCPs per stereo. However, GCP marking took twice as long, because each eligible GCP had to be marked in both collects. Also, the marked pixels were not projected to the same height as the GCP when computing the geolocation error. Because each image in the stereo pair had a different (monoscopic) geolocation error, the two view vectors from the same marked GCP rarely intersected. Instead, the two pixels were projected to a height that minimized the distance between them, see Figure 2. The midpoint of a line that connected the two pixels at this minimum was considered to be the projected location of the GCP. This is the same kind of stereo intersection computed by the software package Socet Set, provided the imaging parameters, e.g. satellite attitude angles and ephemeris coordinates, are not allowed to adjust while the solution is found.

The stereoscopic geolocation error was a vector that pointed from the bisector of closest approach to the GCP truth coordinates, see Figure 2. Only the full geolocation error was computed for a stereo; nadir projection becomes ambiguous, since there were two cameras, two perspective centers, etc. Like a monoscopic image, a stereo pair was summarized by the average geolocation error over all GCPs. However, this average error had both horizontal and vertical components as seen by a local observer. It is customary to study the average errors with separate horizontal and vertical statistics, since the two components were handled in a slightly different fashion. While monthly measurements were taken, quarterly statistics were used to assess the horizontal and vertical components of stereoscopic geolocation error.

The horizontal component of an average geolocation error always had a positive magnitude. When all the horizontal biases in a quarter were collected in a bin, the aforementioned formula was used to take the 90^{th} percentile of all the magnitudes. This 90^{th} percentile was a CE90, since each horizontal error component could have pointed in any direction. The

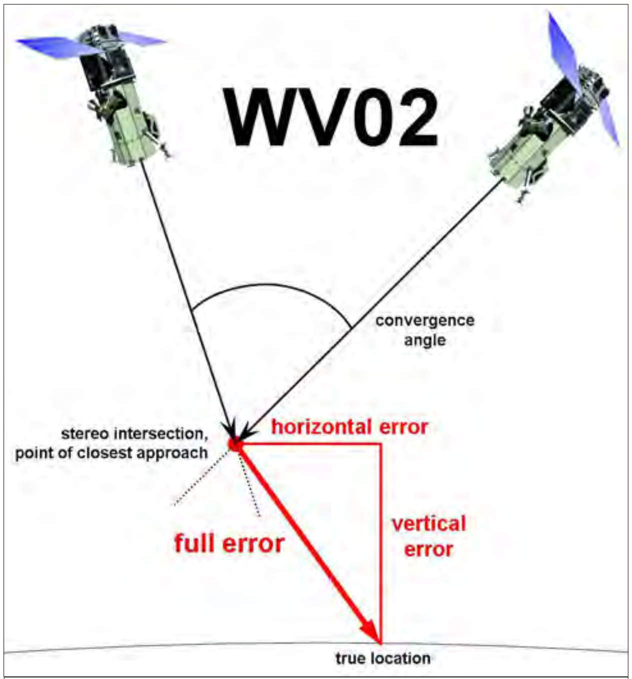

Figure 2. Stereoscopic geolocation error for WV02. The two rays rarely intersect because both images have a different monoscopic geolocation error.

CE90 of a quarter could be called the horizontal CCAP metric for that quarter.

The vertical component of an average geolocation error could be positive or negative, depending on whether the stereo intersection was below or above the GCP. When plotted, the sign of the vertical error was retained. However, when the 90th percentile was taken, the absolute values of the vertical errors were used. This reflected how large vertical error was undesirable, regardless of sign. The resulting vertical CCAP metric was an LE90, since only one (vertical) direction had been considered.

RESULTS

Monoscopic Geolocation Accuracy of QB02, WV01, and WV02

The monoscopically derived geolocation accuracy of QB02 can be seen in Figure 3. Each monoscopic image is a single point plotted at the time of collection against the magnitude of the average geolocation error. The CCAP metrics for both the full errors and nadir projected errors are shown; for clarity, only the nadir projected data points have been plotted in the background. The quarterly 90th percentiles were uniform over the last 2 years, despite large variations in the number of images per quarter. The CCAP metric of full error always stayed between 15 and 21 meters, while the nadir projected metrics were slightly lower, always between 13 to 18 meters. Overall, the trend over the last 2 years was flat. Note how the top 10% of average errors in each quarter could exceed 30 meters; 3Q2010 held the highest, an 80 meter image.

The monoscopic statistics for WV01 are noticeably better than those for QB02. Figure 4 shows the last 2 years of quarterly CCAP metrics for WV01. WV01 almost always had more strips per quarter than QB02, the only exception was 1Q2010. The quarterly CCAP metrics were far lower for WV01; full error was always between 4.3 to 5.5 meters, and nadir projected error was similarly between 3.6 and 4.9 meters. There was a slight downward slope to both error trends, showing a gradual improvement from nearly 5 meters at nadir initially to just 3.6 meters at nadir by 4Q2010. This was the result of improved ground processing for WV01 attitude data, using lessons learned from WV02. The worst average error within the last two years was just 8.3 meters at nadir (2Q2010), an order of magnitude better than QB02.

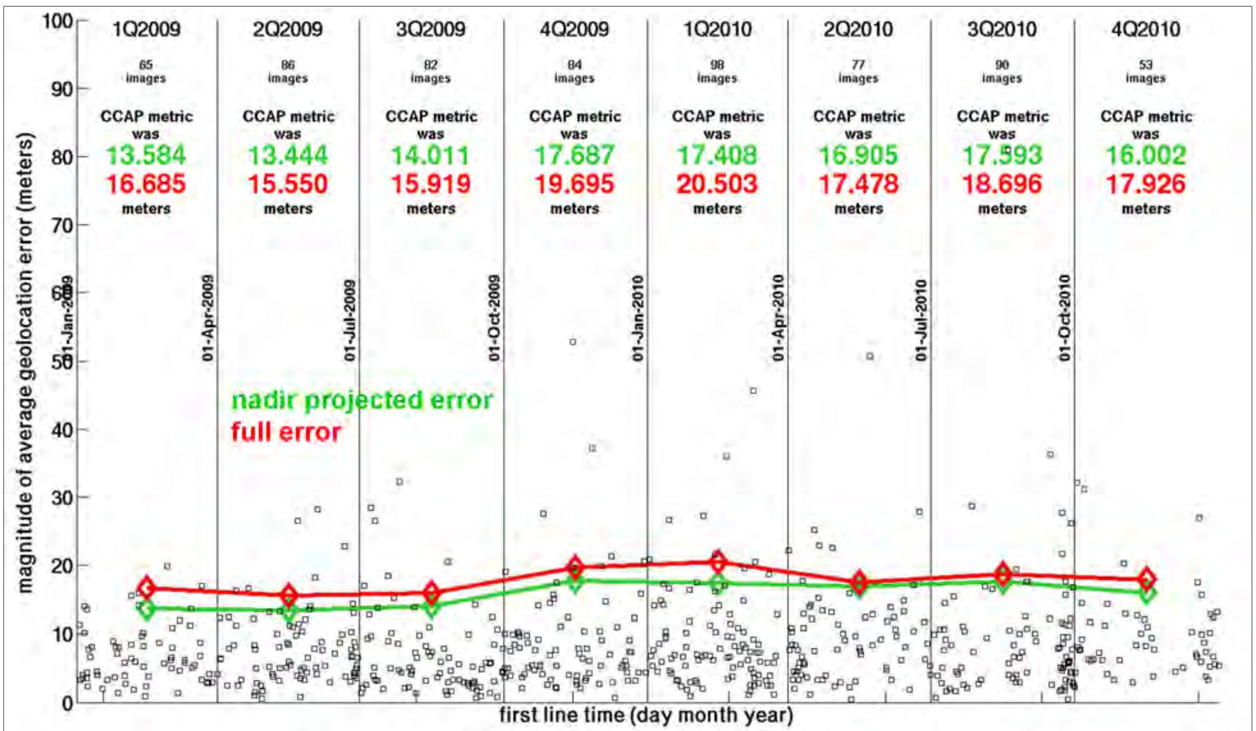

Figure 3. The monoscopic geolocation accuracy of QB02 over the last two years, binned into quarterly statistics. Only data points from the nadir projected statistics are shown. The trend was essentially flat.

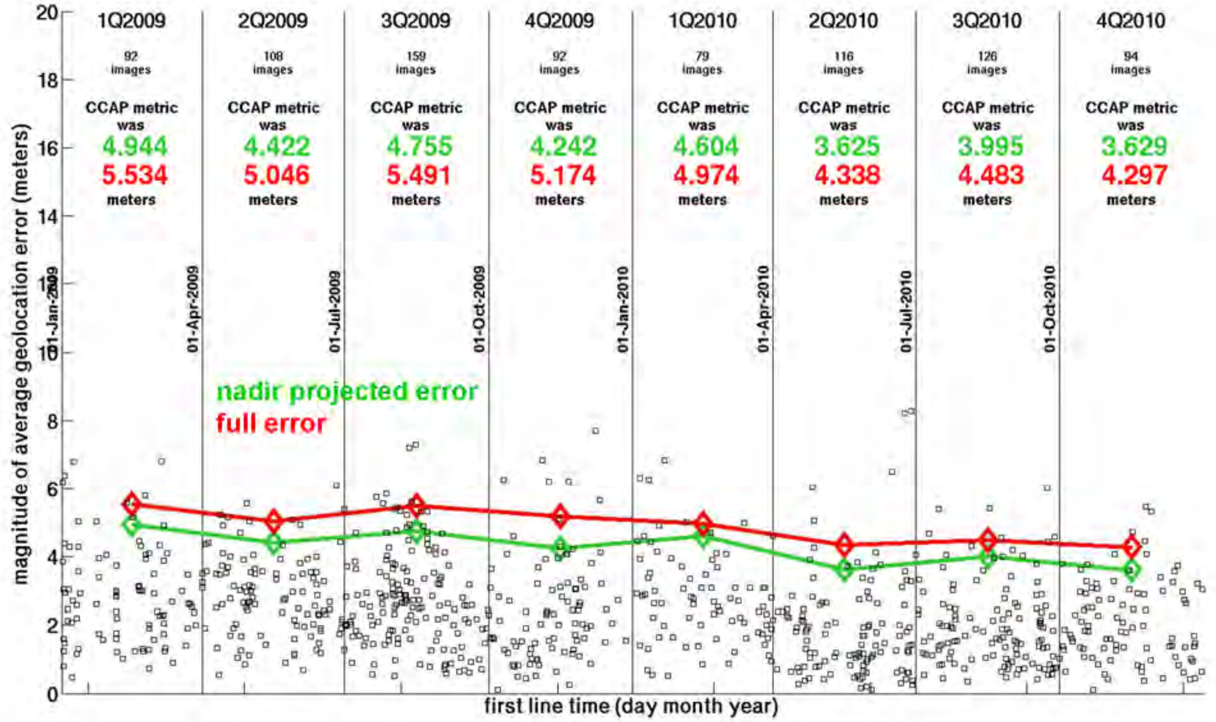

Figure 4. The monoscopic geolocation accuracy of WV01 over the last two years, binned into quarterly statistics. There was a slight downward trend; performance improved with better ground processing of attitude.

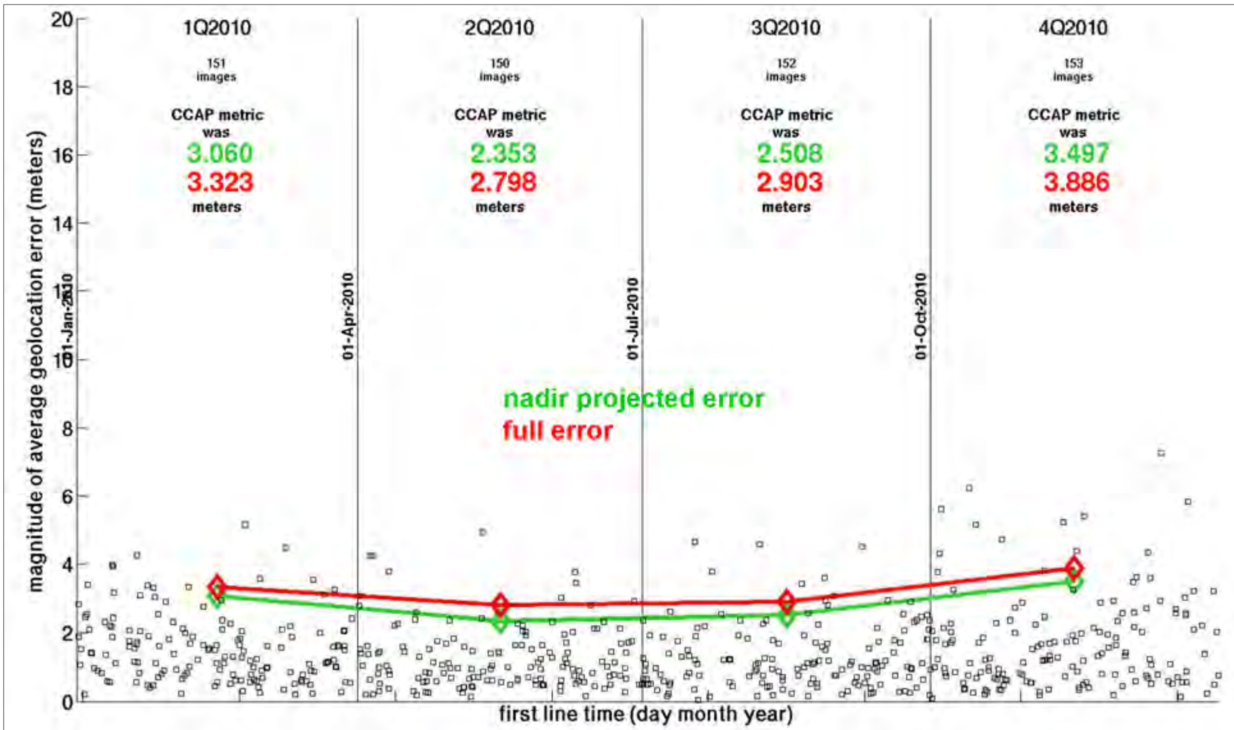

Figure 5. The monoscopic geolocation accuracy of WV02 over 2010, binned into quarterly statistics. Performance was best during the spring, summer, and early fall, where the nadir projected average error dipped below 3 meters.

WV02 represents further improvement in geolocation accuracy beyond WV01, see Figure 5. WV02 had the most geocal images of any satellite in 2010, 150 or more per quarter. Only data after 1 Jan 2010 is shown because that was the end of the calibration period following launch, when imagery was made publically available. WV02 outperformed both QB02 and WV01 throughout 2010; the full error CCAP metrics always fell between 2.8 and 3.9 meters, and the nadir projected CCAP metrics ranged from 2.4 to 3.5 meters. The worst quarter for WV02 (4Q2010, 3.5 meters at nadir) was slightly better than the best quarter for WV01 (2Q2010, 3.6 meters at nadir). Even the worst WV02 image was just 7.3 meters at nadir (4Q2010), a meter better than the worst outlier for WV01. The incredibly good performance of WV02 during the central quarters of 2010 established a new accuracy record for DigitalGlobe's constellation.

Stereoscopic Geolocation Accuracy of WV02

The stereoscopic geolocation accuracy results for WV02 are plotted the same way as the monoscopic results, with one point per one stereo placed at the intersection of acquisition time and average error. There were far fewer WV02 stereos than monoscopic strips available in each quarter of 2010, see Figure 6. No quarter exceeded 55 stereos, about a factor of three less than the 150 strips per month shown in Figure 5. Stereo analysis of WV02 started 1 Mar 2010, so 1Q2010 only has data in the final third.

The horizontal component of stereoscopic geolocation error ranged from nearly the same size as the full error from the monoscopic analysis to about a meter higher. This was expected, since the stereo intersections were always within a few meters of the associated monoscopic projection. For the last three quarters completely filled with data, the horizontal CE90 was always between 3.8 to 4.6 meters, and the trend was essentially flat. The great, 2.6 meter performance of 1Q2010 was likely happenstance, since no average error was above 3 meters. All other quarters contain higher average errors, and are probably more representative of what customers would find. The worst horizontal error component seen in 2010 was 6.0 meters, over a meter better than the 7.3 meter outlier from the WV02 monoscopic analysis. Note that nadir projected statistics were not prepared because of the inherent ambiguity of stereo collects.

The corresponding vertical components of the same stereoscopic geolocation errors are plotted in Figure 7. Vertical errors were both positive and negative for all four quarters. The absolute values of the vertical errors were

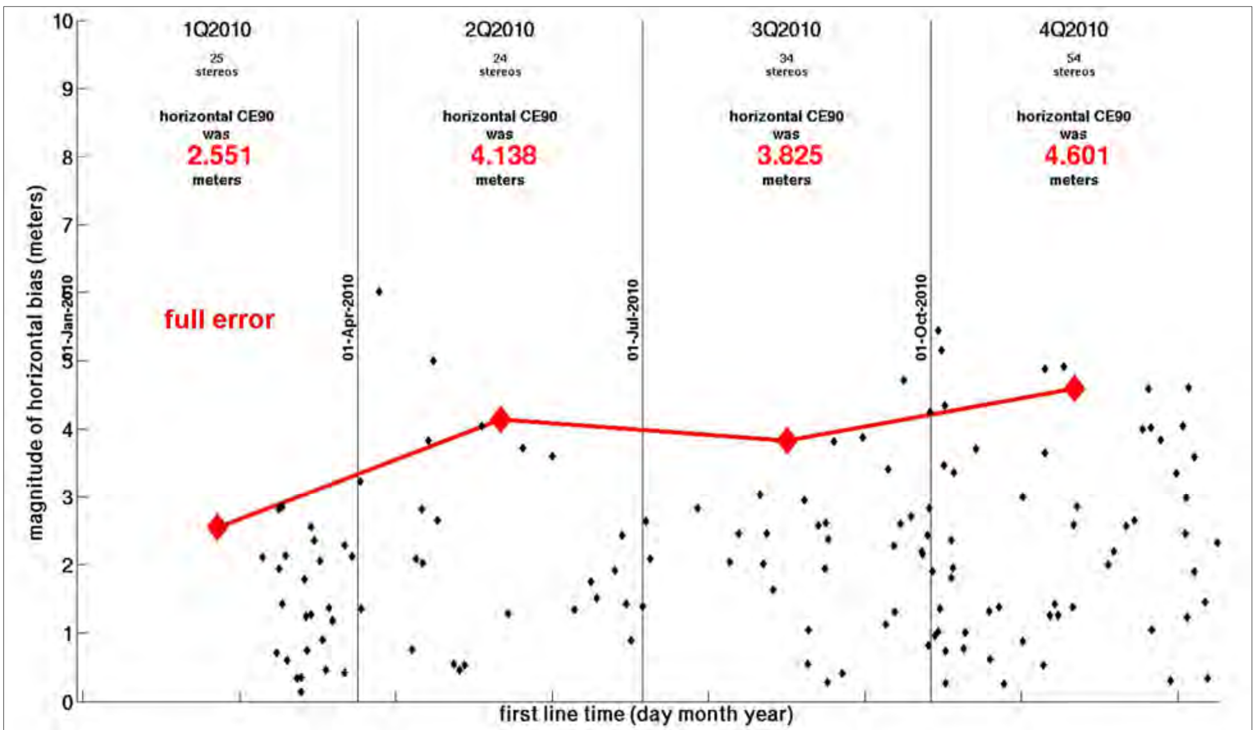

Figure 6. The horizontal component of average geolocation error measured in WV02 stereo pairs during 2010. 1Q2010 only had data in the final third. The horizontal CE90 can exceed 4 meters, a little higher than the full error statistics from the monoscopic study of WV02.

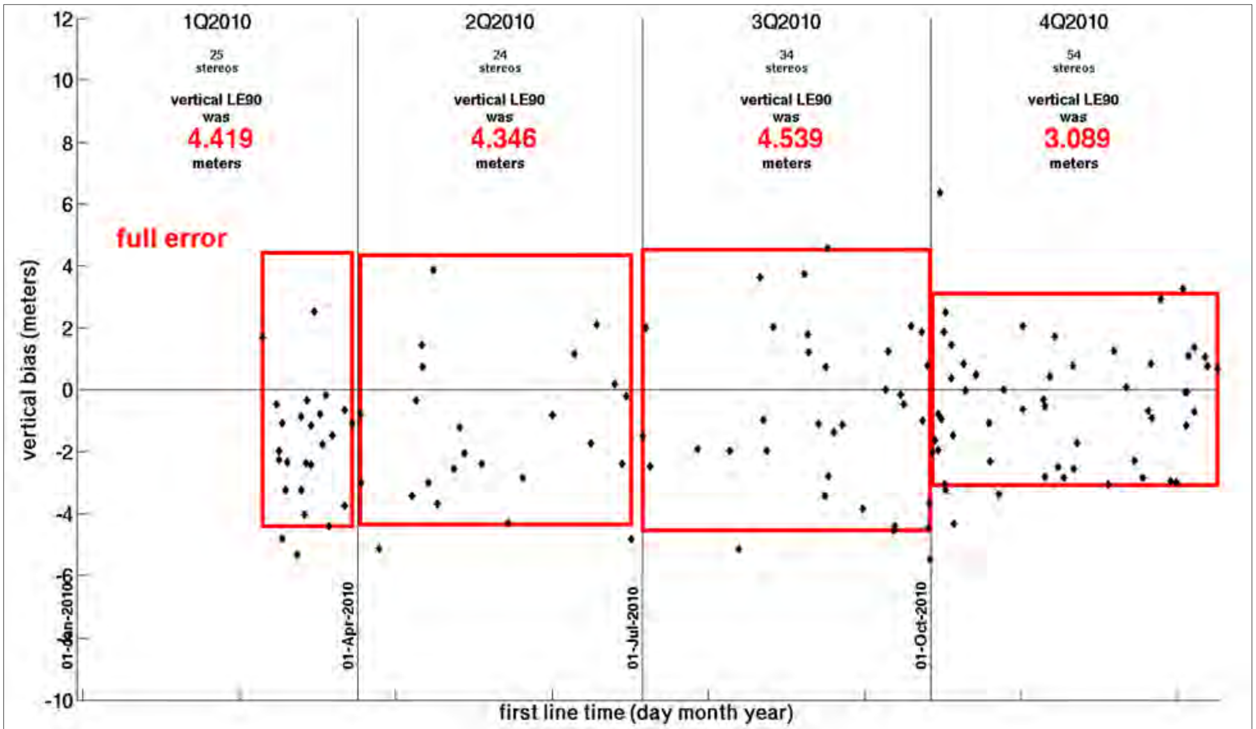

Figure 7. The vertical component of average geolocation error measured in WV02 stereo pairs during 2010. 1Q2010 only had data in the last month, March. The rectangle in each quarter extends out to the LE90 in both the positive and negative directions, since the vertical error could have either sign.

used to compute the LE90 for each quarter. A rectangle extends to plus and minus the 90th percentile value, to indicate how the LE90 includes both signs of error. (The rectangle merely encloses all points in the time direction.) The LE90 trend was a stable plateau near 4.5 meters for nearly the entire year, closing in to 3.1 meters in the fourth quarter.

CONCLUSIONS

The monoscopic geolocation accuracy of DigitalGlobe's satellite constellation has been monitored over the last 2 years with monthly GCP measurements arranged in quarterly bins. Over the last 2 years, the CCAP metric for QB02, the oldest satellite, was always between 13 to 18 meters at nadir. WV01 had better performance over the last 2 years than QB02; the quarterly CCAP metric for WV01 ranged between 3.6 to 4.9 meters at nadir. WV02, the newest satellite, had the best monoscopic performance of all during 2010, with nadir projected CCAP metrics always between 2.4 and 3.5 meters at nadir.

The stereoscopic geolocation accuracy of WV02 was also investigated with monthly GCP measurements binned into quarterly statistics. Throughout 2010, the horizontal component of geolocation error always had a quarterly CE90 between 2.6 and 4.6 meters. The quarterly LE90 of WV02 stereos varied even less during 2010, from 3.1 to 4.5 meters.