JPL

INTEROFFICE MEMORANDUM

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SUBJECT: RPC Fitting for Quickbird

Section 1: Introduction

The purpose of this memo is to document the software and testing that has been done to improve the RPC coefficients supplied with QuickBird. Although the focus is on QuickBird, the same software can be used for other instruments.

Section 2: QuickBird

QuickBird has several levels of processing available for its products, ranging from basic imagery to orthorectified data with a claimed accuracy of 2.5 meter absolute (RMSE). The pricing of the products follows the level of processing, with basic imagery being the cheapest and the custom orthorectified the most expensive. (See [1]).

The basic imagery is radiometrically and sensor corrected, but not geometrically corrected nor mapped. In addition to the attitude, ephemeris, and camera model, Rational Polynomial Coefficients (RPCs) are supplied. The RPCs is a re-parameterization of the rigorous sensor orientation model, and has close to the same accuracy and errors. In particular while the camera interior orientation is determined to high accuracy, the exterior orientation is based solely on measured position and attitude, i.e. there is no ground truth used for the basic imagery product (See [2]).

If the supplied RPCs are used along with a high quality DEM to orthorectify the basic imagery, errors can be expected. The errors are typically something like 20 m (see [1] and [2]), however they can be much larger. In the test data we used, the initial errors are 400 – 500 meters.

To improve the supplied RPCs, we match the imagery against Controlled Image Base (CIB). The DEM used is the Shuttle Radar Topography Mission (SRTM).

Section 3: Controlled Image Base (CIB)

The Controlled Image Base (CIB) is unclassified digital imagery produced from SPOT commercial imagery that that been orthorectified using the DTED (see [3]). The imagery has a 5 meter resolution. The horizontal accuracy target for the CIB is 23 meters (90% circular error).

Section 4: Shuttle Radar Topography Mission (SRTM)

The SRTM DEM is reported at 30 meter resolution. The requirements for the SRTM data are an absolute height error of 16 meter, relative height error of 10 meter, absolute geolocation error of 20 meter, and relative geolocation error of 10 meter (all at 90% circular error). A detailed accuracy assessment showed that these requirements are met, and in many cases exceeded by a factor of 2 (see [4]).

Note that the original SRTM data is reported relative to mean sea level, however the heights used in the RPCs are relative to WGS-84 ellipsoid. This means that the original SRTM data needs to have a vertical Datum added to it before using it in the processing. This has occurred for the data used in this memo.

Section 5: Test Data

The test data used was the QuickBird basic imagery product acquired May 5, 2003. This data has particularly large errors in it, about 500 meters (700 QuickBird pixels in the sample direction, of about 60 cm resolution).

Section 6: Software

Software was written to improve the RPCs supplied with the Quickbird basic imagery product. The software is a subset of the MISR Geometric Calibration Software. This software was adapted to work in the VICAR environment. The software has detailed documentation generated by doxygen, available at http://macsmyth.jpl.nasa.gov/CartLab/index.html.

Section 7: Algorithm

To improve the RPCs supplied with the QuickBird basic imagery, we do image matching between the CIB and the QuickBird imagery. Specifically we:

1. Since the CIB is as a much coarser resolution than the QuickBird data (5 meter vs. about 60 cm), we first average the QuickBird imagery to roughly the CIB accuracy.[1]
2. Using the current set of the RPC parameters, generate an orthorectified image. This uses the SRTM as the DEM source (with vertical datum added to give heights relative to WGS-84). We generate the orthorectified imagery at the same resolution as the CIB.
3. Generate a grid of points over the orthorectified imagery. This is configurable, but the default is to generate a grid point every 15 pixels in both the line and sample direction.
4. For each grid point, use a feature detector in the neighborhood of the point to find

1 We average rather than doing something less computationally expensive such as subsetting (e.g.,, take every 10^{th} pixel) because it gives better quality imagery for doing image matching.

the location with the best feature to match. This is configurable, but the default is to use a Forstner feature detector, and select the point with the greatest weight.

5. For each feature, do image matching between the CIB and the orthorectified QuickBird data. We'll talk more about the image matching in the next section, but the results of these is that for points with successful matching we get conjugate points and and estimate of the error in the image matching (typically 0.1 – 0.5 pixels).
6. Do a weighted least squares fit to determine updated RPC parameters. We fit for only a subset of the RPC parameters. For now, we restrict ourselves to fitting for RPC numerator parameters only, so we can use a linear least squares fit. The weighting used in the least squares fit is 1/(image matching error estimate)
7. Using the updated RPC parameters, look for blunders in the image matching results from step (5), and remove them. We'll describe the details of this is later section.
8. Repeat the least squares fit in (6), but without the blunders we found in (7). This gives updated RPC parameters.
9. Iterate steps 2 – 8, until the change in the RPC parameters is sufficiently small.

There is a further refinement done to this algorithm. For the example we are looking at, there is large initial error in the orthorectified imagery – on the order of 600 meters. This is larger than the search window we want to use in image matching, so we use an image pyramid approach:

1. Average the CIB and QuickBird imagery to a coarse enough resolution that the expected difference between the two images fit with the image matching window (default is 15 pixels).
2. Do the algorithm mentioned above, but only fit for the line and sample offset coefficients. Also, skip the blunder detection step since we only need an approximate correction.
3. Repeat step 1 and 2, but now the expected difference between the two images is the average difference we found while doing image matching (for example, on the first iteration we might have estimated an error of 1000 meters. In the first iteration, image matching had an average difference of 600 meters. So in the second, we chose a averaging factor so that 500 meters fits in our image matching window. In the second iteration, the average image matching difference might have been 400 meters, which is the difference used in the third iteration).
4. Once the difference found in image matching fits into the image matching window at the full CIB resolution, stop this “coarse fit”, and proceed to a “fine fit”. The fine fit is done at full CIB resolution, and a larger set of RPC parameters are fitted for.

Section 8: Image Matching

To do image matching, we use two different image matchers.

A cross correlation matcher is used first. This performs a correlation between the reference and new imagery, using a given target window size. The correlation is performed over a larger template in the reference imagery, varying the location of the center of the target window over the template window. The location that gives the largest correlation gives the conjugate point between the reference and new imagery. Two checks are made to try to prevent blunders. The variance of the template is measured in the reference imagery, and it must be larger than a given threshold. In addition, the correlation between the target and the template must exceed a threshold. The various parameters are all configurable, but the default values are:

Parameter	*Default Value*
Template size	37 x 37 pixels
Target size	9 x 9 pixels
Minimum correlation	0.3
Minimum variance	0 (e.g., don't do this check)

For points that have a successful cross correlation match, we then try a least square match. The least squares matcher is a nonlinear least squares matcher that attempts to determine the parameters needed to do a affine transformation + linear scaling of the radiance, i.e., we want:

$$g'(i,j) = h_0 + h_1 g(a_0 + a_1 i + a_2 j, b_0 + b_1 i + b_2 j)$$

Where g is the radiance in target and g' is the radiance in the template. The target and template come from the reference and new imagery where we first apply a low pass filter (with kernel (1, 1, 1), (1, 2, 1), (1, 1, 1)). The parameters of the LSM are configurable, but the default values used are:

Parameter	*Default Value*
Target and Template Size	21 x 21 pixel
Precision Goal	0.0625
Precision Requirement (i.e., matching fails if we don't achieve this)	0.2
Max sigma (largest error in a_0 and b_0 in an iteration of the LSM)	0.5
Radiometric Uncertainty Factor (largest error in h_0 in an iterator of LSM)	2.0
Precision minimum geometric goal	0.15

Precision minimum radiance goal	1

As a simple visual inspection will verify, the CIB and the QuickBird imagery look fairly different from each other. This results in a large number of failures of the least squares matcher. In the test case, roughly 3 out of 4 points that had a cross correlation solution did not have a successful least squares match. There are two approaches:

1. For point that have the least squares matcher fail, simply toss them out as potential blunders. This greatly reduces the number of conjugate points, but also reduces the number of blunders.
2. For points where the least squares matcher fails, use the cross correlation results.

The cross correlation results are only to the nearest pixel, so this gives a error estimate of 0.5 x 0.5 pixels, vs. the typical least squares error estimate of 0.1 x 0.1. What this means is that in the RPC weighted least squares matcher, the cross correlation results are given a much lower weight than the LSM. However, there are significantly more of them, so they can affect the results.

Section 9: Blunder Detection

As has already been mentioned, there is a considerable difference between the QuickBird and CIB imagery. This leads to a large number of blunders.

A couple of different approaches were tried, but what was settled on was to just remove all the outliers:

1. Calculate the standard residuals between the location of conjugate image matching points as predicted by the updated RPC coefficients vs. that determined by image matching.
2. The residuals are weighted by the image matching error. This will underestimate the actual error by a considerable degree because it doesn't account for the accuracy of the CIB. The typically image matching error will be 0.1 – 0.5 pixels, while the CIB is estimated to have an error of 23 meter or about 4 – 5 pixels. So we will estimate the standardized residuals by:
   - Calculate the standard residuals using the image matching weighting
   - Calculate the average of all the standard residuals
   - Scale the standard residuals so the average is now 1.0
3. Now, remove all the points with a standard residual greater than threshold. The threshold is configurable, with a default of 3.0.

Section 10: Parameters to Vary

There are two approaches to determining what parameters to vary. The first is to try to get as good agreement as possible with the CIB. To do this, a large number of the numerator parameters are fitted, such as the 10 parameters that don't involve the height term.

The second approach is to say that the interior orientation of camera has been well determined by the instrument team. The only error source is in the exterior orientation of the sensor. If this is the case, then we want to minimize the number of parameters we vary – the idea being we are more likely to make thing worse than improve them. The higher order terms in the RPC polynomial come larger from the nonlinearity of the optics (combined with the curvature of the Earth). In this case, we vary the constant terms, plus perhaps the affine terms. This is the approach taken in [2].

I think the second approach is the better one. The accuracy of the QuickBird instrument is potentially much better than the 23 meter error expected in the CIB. By trying to match it too closely to the CIB, we are more likely to degrade the accuracy of the QuickBird to the CIB accuracy than we are to improve it.

Correcting for the constant terms (a_0 and c_0) corrects for static position and attitude error in the ephemeris and attitude. Correction for the affine terms largely correct for time dependent errors in the exterior orientation. (see [2])

The particular test case we used has fairly large errors. For this particular case, we also looked at varying the linear height term (a_3 and c_3). This was to compensate for what looked like a larger roll error. I'm not sure if this is needed in general or not, we'll need to look at more cases to determine if the height term is important or not.

Section 11: Diagnostics

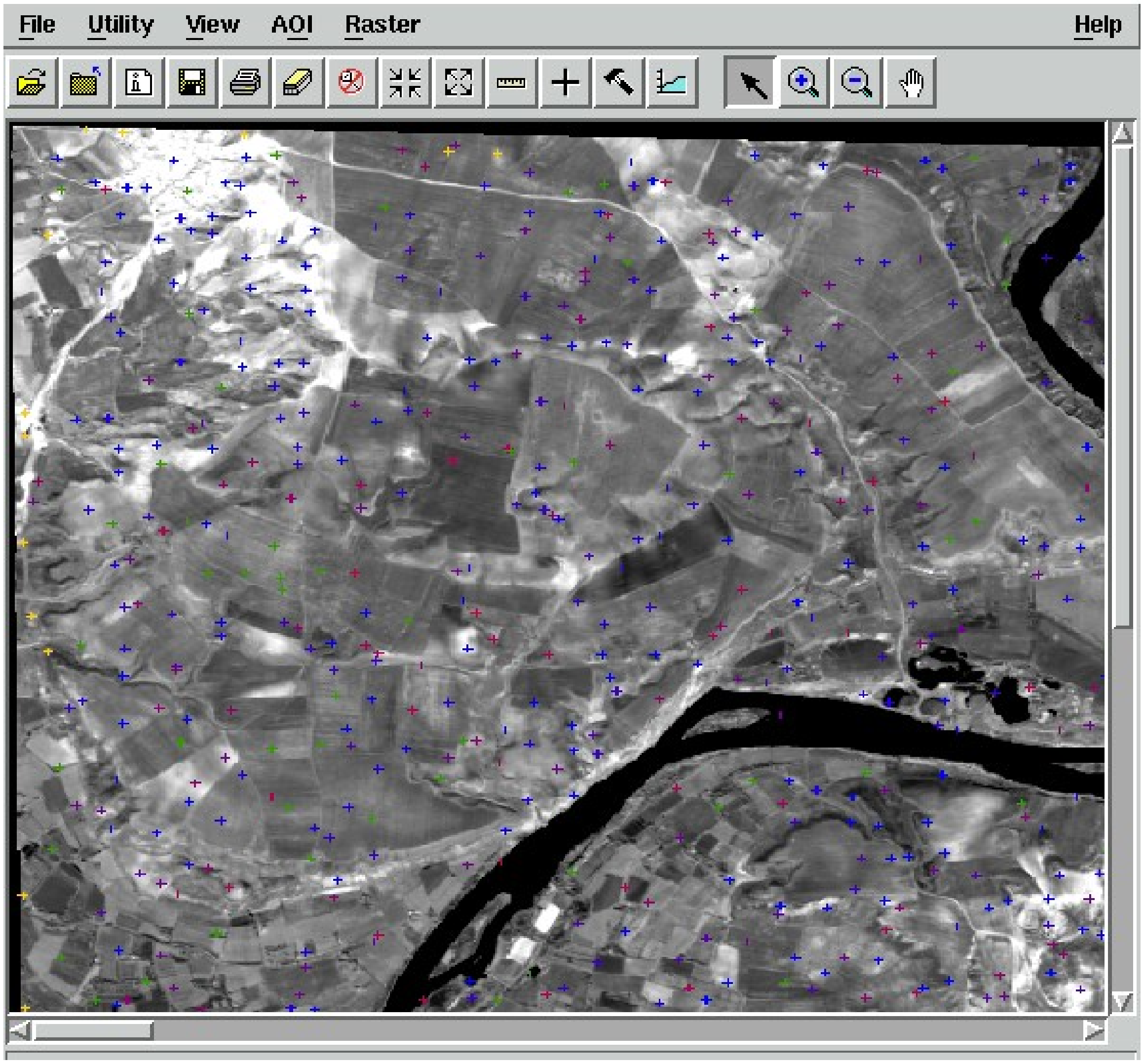
A few diagnostics are used to determine how good of a job we are doing in improving the RPCs.

The simplest is just the average difference between the image matching done between the CIB and QuickBird. This average can be influenced by blunders, so we also calculate the median value, and generate histogram of the differences to try to give some quick idea of the spread.

The next diagnostic is to visually inspect the CIB vs. the orthorectified QuickBird data. This is done in the GIS tool ERDAS imagine, allowing a comparison between the two images.

To understand the distribution of grid points, we output an image giving the grid points used in the last iteration of the algorithm. These grid points are color coded to indicate how different the CIB and QuickBird data are, or for grid points where image matching failed we use colors to indicate why it failed. The grid points are outputted for both the CIB and QuickBird points, and can be overlaid on the imagery in Imagine. See a sample of this below:

Finally, when doing two different runs of the algorithm (e.g., varying one subset of RPC parameters vs. another subset) it can be difficult to determine if differences in the RPC coefficients calculated are significant (e.g., what does it mean if parameter 5 varies by



20%?). To visualize this, we can create difference images showing the difference in the calculated instrument line, sample, and total between the two RPCs. This allows us to determine if differences are significant or not.

Section 12: Results

We don't expect the agreement between QuickBird and the CIB to be better than the relative accuracy of the CIB. If we orthorectified QuickBird exactly to ground truth, it would still be different from the CIB since the CIB doesn't match ground truth. The relative accuracy of CIB isn't something I know, but the total error as mentioned before is 23 meters.

There are a few different cases we looked at. The detailed output is listed in the Appendix, and the results summarized in the table.

1. Case 1 – Using the whole QuickBird scene, allowing parameters 0, 1, 2, 3, 4 to vary (the affine + linear height term). Blunder detection was done, and cross-

correlation only image match points were accepted.

2. Case 2 – Like Case 1, but only fit 0, 3 (constant + linear height term)
3. Case 3 – Start with a Vicar job that fits a subset of the full image (5500 samples). Then, fit for 0, 3.
4. Case 4 – Use same subset as Case 3, but use the original RPC corrected only for line and sample offset rather than VICAR calculated RPC.

Case	***Parameters***	***Blunder Detect***	***Ccoor Only***	***Blunders***	***Good Points***	***Median diff CIB***	***Mean Diff Case 1***	***Max Diff Case 1***
Case 1	0, 1, 2, 3, 4	Yes	Yes	2378	6479	11 m	0 QB pixels (about 60 cm)	0
Case 2	0, 3	Yes	Yes	2294	6454	13 m	6 pixel = 3.6 m	13 pixel = 7.8 m
Case 3	0, 3	Yes	Yes	342	1342	30 m	18 = 10 m	108 = 65 m
Case 4	0, 3	Yes	Yes	434	1289	14 m	9 = 5 m	16 = 9 m

Appendix A

Case 1:

```
Removed 2378 blunders
Have 6479 good points
Average diff: 21.3074 m
Median diff:  11.3206 m
90% <= :      55.2269 m
Minimum diff: 0.154581 m
Maximum diff: 103.381 m
Rpc: RPC:
  Line offset:      2934.19
  Line scale:       2921
  Sample offset:    13049
  Sample scale:     14238
  Longitude offset: 44.9534 degrees
  Longitude scale:  0.1239 degrees
  Latitude offset:  35.8606 degrees
  Latitude scale:   0.0209 degrees
  Height offset:    1017 m
  Height scale:     634 m
```

```
  Line Numerator:   0.0174748 -0.148568 -1.13393 -0.0135206 0.003585
6.35242e-05 0.000115861 -0.00286551 -0.00778726 3.88308e-06 -1.26487e-
06 7.88107e-06 3.65929e-05 2.32154e-06 -2.25421e-05 -2.08933e-05
1.8091e-05 3.6393e-07 -9.39815e-07 -4.31269e-08
  Line Denominator: 1 0.00380256 0.00643151 0.00031479 1.84958e-05
-1.98243e-06 -1.16422e-06 -1.92637e-05 7.22401e-05 -1.61779e-05
4.95049e-06 1.26794e-06 0.000190771 -1.57429e-07 2.46815e-05 0.00049166
-5.41022e-07 3.209e-07 1.81401e-05 1.43592e-07
  Sample Numerator:   -0.0104666 0.967772 -0.000429609 -0.0343213
-0.00101994 0.000217572 -6.54969e-05 0.0107384 -5.19453e-06 -1.76761e-
05 -1.21058e-06 0.000106017 5.41226e-06 -3.8968e-06 1.03307e-05
5.84016e-05 3.80777e-08 9.01765e-06 1.65988e-06 -1.19374e-07
  Sample Denominator: 1 -0.000319831 0.000681092 -0.000549762
-2.67977e-06 -6.19388e-06 2.67975e-08 4.76371e-06 -1.47985e-05
-4.23457e-06 1.44009e-08 -1.07213e-06 1.1059e-07 4.10217e-08 -1.69482e-
07 1.08104e-06 0 -2.33038e-07 1.86413e-08 -1.35637e-08

Failed points: 1430
To close to edge:   20
Variance to low:    0
Correlation to low: 1410
Exceed max sigma:   0
Exceed max rad var: 0
Exceed prec req:    0
Move past target:   0
Histogram
> 0 : 3040
> 10 : 1015
> 20 : 503
> 30 : 505
> 40 : 506
> 50 : 466
> 60 : 324
> 70 : 103
> 80 : 13
> 90 : 4
```

Case 2:

```
Removed 2294 blunders
Have 6454 good points
Average diff: 23.4492 m
Median diff:  13.2486 m
90% <= :      58.6481 m
Minimum diff: 0.121249 m
Maximum diff: 89.7556 m
Rpc: RPC:
  Line offset:      2934.19
  Line scale:       2921
  Sample offset:    13049
  Sample scale:     14238
  Longitude offset: 44.9534 degrees
  Longitude scale:  0.1239 degrees
  Latitude offset:  35.8606 degrees
```

```
  Latitude scale:   0.0209 degrees
  Height offset:    1017 m
  Height scale:     634 m
  Line Numerator:   0.0166341 -0.14751 -1.13465 -0.0147229 0.0020018
6.35242e-05 0.000115861 -0.00286551 -0.00778726 3.88308e-06 -1.26487e-
06 7.88107e-06 3.65929e-05 2.32154e-06 -2.25421e-05 -2.08933e-05
1.8091e-05 3.6393e-07 -9.39815e-07 -4.31269e-08
  Line Denominator: 1 0.00380256 0.00643151 0.00031479 1.84958e-05
-1.98243e-06 -1.16422e-06 -1.92637e-05 7.22401e-05 -1.61779e-05
4.95049e-06 1.26794e-06 0.000190771 -1.57429e-07 2.46815e-05 0.00049166
-5.41022e-07 3.209e-07 1.81401e-05 1.43592e-07
  Sample Numerator:   -0.0111547 0.96885 -0.000487887 -0.0356537
-0.000710444 0.000217572 -6.54969e-05 0.0107384 -5.19453e-06 -1.76761e-
05 -1.21058e-06 0.000106017 5.41226e-06 -3.8968e-06 1.03307e-05
5.84016e-05 3.80777e-08 9.01765e-06 1.65988e-06 -1.19374e-07
  Sample Denominator: 1 -0.000319831 0.000681092 -0.000549762
-2.67977e-06 -6.19388e-06 2.67975e-08 4.76371e-06 -1.47985e-05
-4.23457e-06 1.44009e-08 -1.07213e-06 1.1059e-07 4.10217e-08 -1.69482e-
07 1.08104e-06 0 -2.33038e-07 1.86413e-08 -1.35637e-08

Failed points: 1449
To close to edge:   23
Variance to low:    0
Correlation to low: 1426
Exceed max sigma:   0
Exceed max rad var: 0
Exceed prec req:    0
Move past target:   0
Histogram
> 0 : 2649
> 10 : 1208
> 20 : 522
> 30 : 485
> 40 : 516
> 50 : 510
> 60 : 372
> 70 : 157
> 80 : 35
> 90 : 0
Min: 0.000956925
Max: 13.1317
Mean: 5.56446
```

Case 3:

```
Removed 342 blunders
Have 1342 good points
Average diff: 35.781 m
Median diff:  30.7048 m
90% <= :      73.2937 m
Minimum diff: 0.278719 m
Maximum diff: 98.3295 m
Rpc: RPC:
  Line offset:      2881.23
```

```
  Line scale:       2921
  Sample offset:    13750.5
  Sample scale:     14238
  Longitude offset: 44.9534 degrees
  Longitude scale:  0.1239 degrees
  Latitude offset:  35.8606 degrees
  Latitude scale:   0.0209 degrees
  Height offset:    1017 m
  Height scale:     634 m
  Line Numerator:   0.177406 0.351971 -1.13998 0.00535028 -0.0223615
6.35242e-05 0.000115861 0.651193 -0.0170367 3.88308e-06 -1.26487e-06
0.281382 -0.0120895 2.32154e-06 -0.0187892 -0.00192203 1.8091e-05
3.6393e-07 -9.39815e-07 -4.31269e-08
  Line Denominator: 1 0.00380256 0.00643151 0.00031479 1.84958e-05
-1.98243e-06 -1.16422e-06 -1.92637e-05 7.22401e-05 -1.61779e-05
4.95049e-06 1.26794e-06 0.000190771 -1.57429e-07 2.46815e-05 0.00049166
-5.41022e-07 3.209e-07 1.81401e-05 1.43592e-07
  Sample Numerator:   0.111512 1.64657 0.0885185 -0.0477845 0.230635
0.000217572 -6.54969e-05 0.826355 0.00866377 -1.76761e-05 -1.21058e-06
0.320986 0.0112633 -3.8968e-06 0.147509 0.00143205 3.80777e-08
9.01765e-06 1.65988e-06 -1.19374e-07
  Sample Denominator: 1 -0.000319831 0.000681092 -0.000549762
-2.67977e-06 -6.19388e-06 2.67975e-08 4.76371e-06 -1.47985e-05
-4.23457e-06 1.44009e-08 -1.07213e-06 1.1059e-07 4.10217e-08 -1.69482e-
07 1.08104e-06 0 -2.33038e-07 1.86413e-08 -1.35637e-08

Failed points: 184
To close to edge:   25
Variance to low:    0
Correlation to low: 159
Exceed max sigma:   0
Exceed max rad var: 0
Exceed prec req:    0
Move past target:   0
Histogram
> 0 : 217
> 10 : 277
> 20 : 168
> 30 : 145
> 40 : 118
> 50 : 118
> 60 : 136
> 70 : 101
> 80 : 54
> 90 : 8
Min: 0.0162402
Max: 108.381
Mean: 18.3761
```

Case 4:

```
Removed 434 blunders
Have 1289 good points
Average diff: 25.799 m
```

```
Median diff:  14.3214 m
90% <= :      60.5707 m
Minimum diff: 0.257292 m
Maximum diff: 86.1256 m
Rpc: RPC:
  Line offset:      2937.13
  Line scale:       2921
  Sample offset:    13044.5
  Sample scale:     14238
  Longitude offset: 44.9534 degrees
  Longitude scale:  0.1239 degrees
  Latitude offset:  35.8606 degrees
  Latitude scale:   0.0209 degrees
  Height offset:    1017 m
  Height scale:     634 m
  Line Numerator:   0.0322705 -0.14751 -1.13465 0.00512247 0.0020018
6.35242e-05 0.000115861 -0.00286551 -0.00778726 3.88308e-06 -1.26487e-
06 7.88107e-06 3.65929e-05 2.32154e-06 -2.25421e-05 -2.08933e-05
1.8091e-05 3.6393e-07 -9.39815e-07 -4.31269e-08
  Line Denominator: 1 0.00380256 0.00643151 0.00031479 1.84958e-05
-1.98243e-06 -1.16422e-06 -1.92637e-05 7.22401e-05 -1.61779e-05
4.95049e-06 1.26794e-06 0.000190771 -1.57429e-07 2.46815e-05 0.00049166
-5.41022e-07 3.209e-07 1.81401e-05 1.43592e-07
  Sample Numerator:   -0.00812904 0.96885 -0.000487887 -0.0327699
-0.000710444 0.000217572 -6.54969e-05 0.0107384 -5.19453e-06 -1.76761e-
05 -1.21058e-06 0.000106017 5.41226e-06 -3.8968e-06 1.03307e-05
5.84016e-05 3.80777e-08 9.01765e-06 1.65988e-06 -1.19374e-07
  Sample Denominator: 1 -0.000319831 0.000681092 -0.000549762
-2.67977e-06 -6.19388e-06 2.67975e-08 4.76371e-06 -1.47985e-05
-4.23457e-06 1.44009e-08 -1.07213e-06 1.1059e-07 4.10217e-08 -1.69482e-
07 1.08104e-06 0 -2.33038e-07 1.86413e-08 -1.35637e-08

Failed points: 151
To close to edge:   34
Variance to low:    0
Correlation to low: 117
Exceed max sigma:   0
Exceed max rad var: 0
Exceed prec req:    0
Move past target:   0
Histogram
> 0 : 516
> 10 : 190
> 20 : 97
> 30 : 101
> 40 : 127
> 50 : 121
> 60 : 86
> 70 : 44
> 80 : 7
> 90 : 0
Min: 0.0232624
Max: 15.8234
Mean: 8.68703
```

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