SRTM REGISTRATION FOR ELECTRO-OPTIC SATELLITE IMAGES WITHOUT GCP

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ABSTRACT:

This paper presents a simple methodology for accurate registration of the available elevation data sources, such as SRTM and ASTER DEM, to high resolution satellite images. For this purpose, widely used rational polynomial functions are utilized to project a point in the elevation data onto the satellite image. These projections are then interpolated in the image domain by using quadratic surface fitting. Possible hole points (empty pixels) are eliminated by using overlapping patches. The errors in SRTM data and satellite image geo-location are reduced by the help of tie points. The experimental results indicate better geo-location accuracy compared to the original satellite RPC's could provide. The proposed approach provides a good initial position estimate for each pixel in both stereo satellite images with no ground control points (GCPs), possibly resulting in fast convergence for expensive surface generation iterations and fast stereo match point detection.

1. INTRODUCTION

Modern Earth Observation Satellites (EOS) provide sub-meter resolution and images are in hundred mega-pixels range. The utilization of along-track stereo imaging provides massive amounts of data, which result in very expensive computations, especially for DTM/DSM generation.

Sub-meter geo-location and elevation accuracies require rigorous satellite models (which are not made available by data providers), or non-linear projection information, namely *rational polynomial coefficients* (RPCs), that are provided by the images, and ground control points (GCPs) collected from the field of interest.

Terrain reconstruction is often based on a convex optimization scheme, which optimizes the geodetic coordinates by minimizing the projection errors with respect to the stereo correspondences [*Di 2001*]. The common approach is to start the iterations with very coarse initial estimates, such as "average altitude of the region of interest", which is reported to be sufficient from both convergence speed and accuracy points of view. However, this conclusion is empirical, since the projective relation defined by the RPC's is non-linear. Although the derivatives can be computed analytically, the error surfaces are quadratic only in the image coordinates, not in geodetic coordinates.

Hence, an acceptable initial estimate should provide faster convergence and avoid possible trapping in false local minimas in RPC reconstruction.

It is known that RPC coefficients of modern satellites are biased to yield a few meters of mislocation [*Dial 2002a*]. The usage of GCPs is required for bias elimination. The geolocation error power is concentrated on the constant bias term; thus, even a single GCP might provide significant improvement in the

geolocation accuracy [*Dial 2002a, 2002b, Jacobsen 2008*]. However, GCP collection is a time consuming and expensive task, which requires advanced devices for accurate measurements.

On the other hand, there are widely known and freely available sources of terrain data, such as SRTM [*Farr 2007*] and ASTER DEM. Surprisingly, efforts to utilize these sources are limited [*Arévaloa 2008*, *Gonçalvez 2007, Papasaika 2008*]. The common approach for such exploitation is to generate a sparse point cloud from the stereo images and then find the transformation that registers the point cloud to SRTM. When no GCPs are used, the errors in the projection functions remain and these errors are propagated to the sparse reconstruction, with possible amplification during the triangulation. A recent study [*Gonçalvez 2008*] presented an approach to register SRTM with ALOS images without DEM generation. However, level 1B2 images (which are already geo-referenced) are used for that purpose [*Gonçalvez 2008*].

This paper presents a method to obtain good initial estimates for each pixel of a low level satellite image (only with radiometric corrections), by using freely available SRTM data. The method is then extended to utilize stereo images for an improvement in geolocation accuracy.

The scope of this text is limited to registration (methodology and accuracy) only. The effect on reconstruction speed is left to another study.

2. METHODOLOGY

2.1. Object-to-Image SRTM Registration

The proposed algorithm uses the data vendor provided RPCs to perform the registration *from the object domain to the image*

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domain. RPCs define the rational polynomial functions that map a real world coordinate to the image domain. Therefore, once we have the RPC coefficients, we have the projection functions. Thus, for each point in the SRTM data, we can find its projection pixel in the image.

It is known that SRTM accuracy is unchanged when 90m resolution SRTM data are upsampled by 3 to obtain 30m resolution, via bi-cubic interpolation [*Keeratikasikorn 2008*]. Therefore, in this study, the SRTM data are upsampled by 3 with bi-cubic interpolation and registration is performed for the upsampled version.

Once the SRTM points are projected onto the image, an interpolation is required to fill the empty pixels. The SRTM data is regularly-sampled (30m or 90m Ground Sample Distance; GSD). On the other hand, satellite images have higher resolution and do not sample the Earth surface on a regular latitude-longitude grid. 1 degree x 1 degree SRTM patches and satellite images are never aligned. In other words, the SRTM grid does not project to another regular grid in the image domain and some SRTM points will fall outside the image, especially for narrow FOV satellite images, such as IKONOS. Thus, an interpolation scheme is required that provides acceptable accuracy, and leaves no empty pixels.

For that purpose, quadratic polynomial surface fitting is applied as follows: For each SRTM point p_s , eight neighbours of that SRTM point are projected to the image domain to define a surface patch sampled at 9 points, together with the centre point p_s (Figure 1). Then the projection points are taken as examples from quadratic polynomials (on image coordinates) that define a height function, a latitude function and a longitude function;

$$F_i = a_i.u^2 + b_i.v^2 + c_i.u.v + d_i.u + e_i.v + f_i \qquad (1)$$

where

u, v = image row and column indexes
$i = 1,2,3$ for height, latitude and longitude.
$a_i, b_i, c_i, d_i, e_i, f_i$ = coefficients of the polynomial

In other words, interpolation functions are defined separately for latitude, longitude and height.
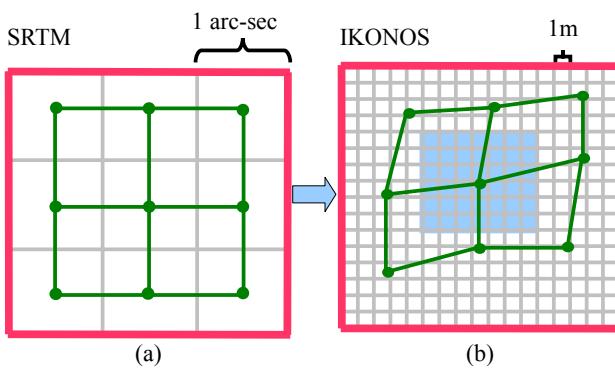

Figure 1. (a) The nine-point SRTM grid and (b) their projections on the satellite image.

The 6 polynomial coefficients are solved by using 9 equations. The empty pixels that lie in the neighbourhood of the centre pixels (blue region in Figure 1) are filled by using the polynomial. Overlapping of the neighbourhoods is forced to avoid empty image pixels. The values of pixels that lie in the overlapping region take the average of the values assigned to them by different patch polynomials

2.2. Elimination of Bias in SRTM-Image Registration

The bias in RPC is mainly due to errors in satellite's position and look direction. The latitude and longitude of the satellite, as well as the look direction, are measured with some error. Although these errors affect directly the inputs of the RPCs (erroneous latitude and longitude), bias correction is usually achieved in the image domain with correction terms for both image coordinates *u* and *v*.

Considering the above-mentioned reasons for projection bias, performing the correction in the object domain may be expected to provide better results. Still, in this study both image and object domain correction are tested.

From the previous experiments in the literature, it is known that the RPC bias is around 5 meters and not larger than 10m (for high resolution satellites, such as IKONOS) [*Dial 2002a, 2002b*]. Additionally, coarse SRTM error figures are available for the entire SRTM coverage [*Rodriguez 2005*]. Thus, one can determine a search region boundary for bias elimination terms.

For bias correction, the following search scheme is adopted:
i. Both images are registered with the method described in 2.1.
ii. A modified optical flow estimation method (Kanade-Lucas Tracker (KLT) [*Bouguet 2000*] with varying pyramids and backward consistency) is used to determine a few number of reliable stereo correspondences (tie points) (Although KLT is not common for correspondence estimation applications, with proper modifications, KLT could provide impressive results with many image correspondences with relatively small computational complexity).
iii. Quantized brute-force search is performed in the search region as follows:

Let $p_1 = (u_1, v_1)$, $p_2 = (u_2, v_2)$ be any correspondence between images I_1 and I_2, and $P_1 = (lat_1, lon_1)$, $P_2 = (lat_2, lon_2)$ be their initial registration vectors (determined by the method described in Section 2.1). The following algorithm is proposed for determining the candidate correction vectors:

For each correction vector $\Delta P = (\Delta_{lat} , \Delta_{lon})$,

   error $= 0$

   For each stereo correspondence pair (p_1, p_2)

      Take single-image registration value P_1 for p_1
      $P'_1 = P_1 + \Delta P$
      p'_2 = Project(P'_1) onto I_2
      error = error + $\| p_2 - p'_2 \|^2$

   end correspondences

end correction vectors

Next, the correction vector with minimum error score is taken as the bias correction vector.

Since the bias has a strong DC term for the entire image, this search is *performed only once* with a few "good" tie points.

Note that, this scheme determines the bias term by projection from image-1 to image-2. One can also perform bias term determination in the inverse direction. Although the average of the two results may be used as the result, in this study, only one-directional bias compensation is performed.

Moreover, if the biases for both images are in the same direction, the benefits of this method are questionable. Still, the SRTM data will behave as anchors, similar to the GCPs.

3. EXPERIMENTS AND RESULTS

3.1. SRTM-Single IKONOS Image Registration

For single-image case, the registration accuracy is evaluated on 123 Ground Control Points (GCPs). The results are as presented in Table 1.

$Value_{GCP}$–$Value_{reg}$	Mean error	σ_{error}	RMS error
Latitude	2.13×10^{-5} °	1.54×10^{-5} °	2.624×10^{-5} °
Longitude	-5.56×10^{-5} °	1.46×10^{-5} °	5.751×10^{-5} °
Height	-5.3 m	4.28 m	6.80 m
Plannimetric	5.28 m	1.64 m	5.28 m
Along UTM X	-4.54 m	1.15 m	4.68 m
Along UTM Y	2.43 m	1.65 m	2.93 m

Table 1. Error figures for SRTM-image registration, for 121 GCPs. IKONOS, (*Hobart region, Australia*)

The errors presented in Table 1 are based on:

i) SRTM plannimetric and height errors, 7.2m and 6.0m, respectively [*Rodriguez 2005*].
ii) RPC projection bias (horizontal: -4.1pixels, vertical: -5.59 pixels)
iii) Imperfection of quadratic interpolation

As it can be observed from Table 1, geolocation errors are mainly systematic shifts, effective in the entire image. At least, they can be corrected by some systematic shifts. When the error vector is investigated, it can be observed that the error is consistent (e.g., in [-4m -5m] range for UTM X) over all GCP points. The only exceptions are the ones that are near the lower and upper lines of the image. In fact, this is a known phenomenon.

RPC projection bias along *u* (vertical image axis) is 1.5 pixels (corresponding to ~1.5m) more than the bias along *v* (horizontal image axis). Axes *u* and *v* are almost aligned with UTM X and UTM Y, respectively. This difference is directly reflected to the error figures in Table 1. On the other hand, it is also noticeable that the errors are smaller than RPC bias. This result may be caused by another cancelling bias in SRTM errors. If SRTM data were error-free, the error figures would have been higher. This fact brings the conclusion that for another region, the bias terms may add up to result in higher error figures.

The relations of geolocation error with terrain height, image row number and image line number are also examined to investigate the uniformity of the error behaviour. The results are given in Figures 2, 3 and 4. Note that, UTM X, UTM Y and Height are not correlated for our GCPs. As it is observed from these graphs, the errors in UTM X and UTM Y are not related to the position in the image, or terrain height, thus the behaviour is close to uniform. On the other hand, the errors along UTM X and UTM Y are quite (and inversely) correlated. The reason for this phenomenon is unknown and to be investigated.
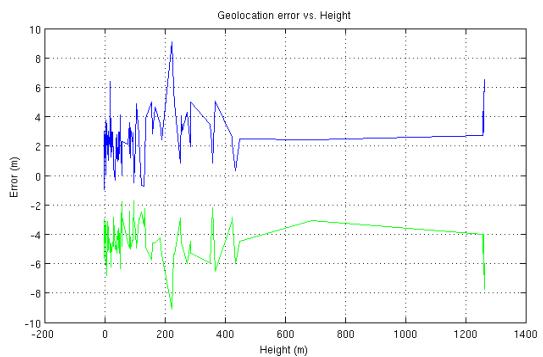

Figure 2. The effect of height in UTM Y (blue) and UTM X (green) errors.
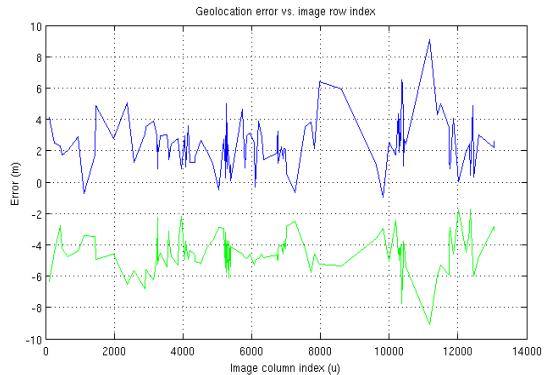
Figure 3. The effect of image row in UTM Y (blue) and UTM X (green) errors.
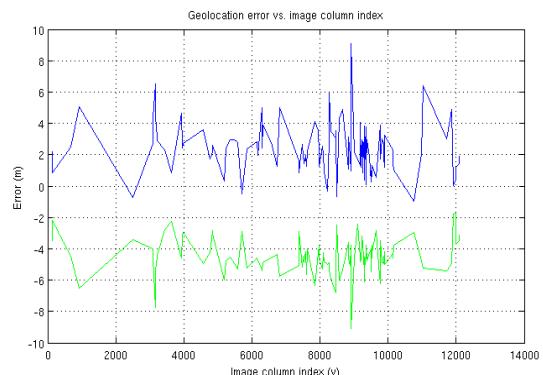
Figure 4. The effect of image column in UTM Y (blue) and UTM X (green) errors.

3.2. SRTM Registration for Stereo IKONOS Images

Bias compensation experiments are conducted in both image domain and the real world (object) domain. The results for object domain correction are better than pixel domain correction and in this paper, we provide only the results for the object domain correction algorithm. Since the errors (RPC bias) are mainly caused by satellite's own mislocation, the corrections in real world coordinates are more effective.

In Table 2, geolocation and height errors are given after bias correction is achieved. For stereo image pair registration, the same region (IKONOS HOBART) is used during these simulations.

Note that, the height error is larger than the SRTM height error. This is acceptable, since the registration error includes the joint effects of SRTM height error, RPC error and interpolation error. SRTM alone, does not provide any information about the satellite image without registration.

	Mean error	σ_{error}	RMS
Latitude	2.43×10^{-5} °	1.53×10^{-5} °	2.873×10^{-5} °
Longitude	-1.76×10^{-5} °	1.46×10^{-5} °	2.288×10^{-5} °
Height	-5.30 m	4.27m	6.8m
Plannimetric error	3.28 m	1.71 m	3.69 m
Along UTM X	-1.43m	1.15 m	1.83 m
Along UTM Y	2.75m	1.65 m	3.21 m

Table 2. Error figures for SRTM-image registration, after bias compensation using stereo pairs, for 121 GCPs. IKONOS, Hobart region, Australia

The increase in the error along UTM Y hints the limits of the bias removal approach.

It should be noted that the error figures in Table 2 are better than the RPC projection errors (~5m plannimetric error) . This result is remarkable, since our errors in SRTM registration include both RPC bias and SRTM geolocation error. The bias terms cancel each other for Hobart region. But they may add up to increase the error power and worsen the registration for some other region. Thus, a more thorough experimental study is required.

4. CONCLUSION

This paper presents a method to register high-resolution EOS images to SRTM data without GCPs. The method can be used for both stereo and single-image cases, providing better accuracy for the stereo case due to the utilization of stereo correspondences. Although the experiments presented in the paper cover only the IKONOS images, this methodology can be applied to other satellite images as long as object-to image projection information is provided.

The SRTM sampling quantizes latitude and longitude, not the ground sample distance, and for the Hobart region, the longitude lines are closer to each other than the latitude lines

are. On the other hand, IKONOS data is not in harmony with the geodetic coordinates. Since the IKONOS RPC coefficients are defined over the [latitude, longitude] grid and parse the earth surface from south to north while the Earth is rotating, the error figures for different regions may change. This change may be more severe along UTM X.

An application of this method could be in stereo correspondence generation. Once the registration is performed, each pixel in one of the image pair can be mapped to its conjugate in the other image with only a few pixels of error. For the urban areas, this error may increase due to building heights or recent changes in the terrain. Even in this case, the region that the conjugate point lies is still bounded to a radius of at most a few ten pixels about the estimated point (for tall buildings) In such a small region, the search is fast. This provides significant processing time savings in stereo correspondence determination, which is a key and time consuming step of surface reconstruction. Our recent preliminary experiments agree with this conclusion, but are left to another text.

Acceptable accuracy for registration is determined by the application. For example, if the registration output will be used for generating initial estimates for stereo (conjugate) pair points, the required accuracy is the radius of the search range of the stereo correspondence extraction algorithm.

For image orthorectification, obviously, more accurate registration results in better orthorectification.

If the registration output will be used as initial geodetic coordinate estimates for surface reconstruction, the registration output must reside inside the correct bowl of the error surface for the optimization cost function. At this point, it is difficult to determine what accuracy is required, since the complicated projection (rational polynomial model) functions results in very high order error surfaces and the projection function's coefficients (RPCs) are different for each scene. Thus, although very coarse initial estimates can provide sub-meter accuracies, it is preferable to generate the initial estimates as accurate as possible. Additionally, even if the accuracy of the initial estimates are unimportant for surface reconstruction, a good initial estimate will fasten the convergence of the reconstruction algorithm.

This methodology may also be useful in applications that do not require sub-meter accuracies and recent changes in elevation (e.g., some cartography, civil engineering applications), without terrain reconstruction.

This study should be considered as an initial step. A proper error analysis that accounts for the effects of SRTM and image accuracies is still required.

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