Abstract—The paper presents details regarding implementation of a novel algorithm for reprojection of MODIS level 1B imagery. The method is based on a simultaneous two-dimensional search in latitude and longitude geolocation fields by using their local gradients. Due to the segmented structure of MODIS imagery caused by the instrument whiskbroom electro-optical design, the gradient search is realized in two steps: inter-segment and intra-segment search. This approach resolves the discontinuity of the latitude/longitude geolocation fields caused by overlap between consecutively scanned MODIS multi-detector image segments. The structure of the algorithm allows equal efficiency with the nearest-neighbor and the bilinear interpolation. A special procedure that combines analytical and numerical schemes is designed for reprojecting imagery near the polar region, where the standard gradient search may become unstable.

The performance of the method was validated by comparison of reprojected MODIS/Terra and MODIS/Aqua images with georectified Landsat-7 ETM+ imagery over Canada. It was found that the proposed method preserves the absolute geolocation accuracy of MODIS pixels determined by the MODIS geolocation team. The method was implemented to reproject MODIS level 1B imagery over Canada, North America and Arctic circumpolar zone in four popular geographic projections: Plate Care (cylindrical equidistant), Lambert Conic Conformal (LCC), Universal Transverse Mercator (UTM) and Lambert Azimuthal Equal-Area (LAEA). It was also found to be efficient for reprojection of AVHRR, MERIS satellite images and general type meteorological fields, such as the North American Regional Reanalysis data sets.

Index Terms—Data processing, gradient methods, image processing, image registration, satellite applications

I. INTRODUCTION

The Moderate Resolution Imaging Spectroradiometer (MODIS) is one of the principal sensors currently operating onboard Terra (since 2000) and Aqua (since 2002) spacecrafts [1]. MODIS provides comprehensive series of global observations of the Earth’s land, oceans, and atmosphere in the visible and infrared regions of the electromagnetic spectrum. These observations are important for studies of terrestrial and aquatic ecosystems, weather forecasting, pollution transport, and many other climate and environmental applications.

The MODIS instrument provides observations in 36 spectral bands ranging in wavelengths from 0.4 µm to 14.4 µm [1, 2]. Two bands are imaged at 250 m resolution at nadir, five bands at 500 m, and the remaining 29 bands at 1 km. At the satellite orbit height of 705 km above the Earth surface, the cross-track scanning ±55° from the nadir direction translates into a 2330 km wide swath. This provides global coverage every 1–2 days with a 16-day orbit repeat cycle.

The MODIS Earth location algorithm [2-4] operates as part of the Level 1 processing system that consists of two phases. The level 1A processing involves unpacking and verifying Level 0 MODIS data received from the Earth Observing System (EOS) Data and Operations System (EDOS), organizing these data into MODIS scan oriented data structures, generating the Earth location data, and producing a data product in HDF (Hierarchical Data Format) EOS standard format. The Earth location data fields (latitude, longitude, elevation) are provided as additional layers in the MODIS geolocation files (MOD03 for Terra or MYD03 for Aqua) that describe explicitly the ground location for each 1 km pixel. All levels of MODIS data are freely available from the NASA Distributed Active Archive Center (DAAC). The level 1B processing produces the radiometric calibration parameters to be applied to the raw detector output contained in the Level 1A data product [5, 6]. The calibrated data are used in subsequent Level 2 processing to derive various geophysical parameters and data products [2].

The higher levels of MODIS land products (Level 2G and Level 3) are released in the Sinusoidal (SIN), Integerized Sinusoidal (ISIN), or Latitude/Longitude grid (0.05° or coarser spatial resolution) projections [2, 7]. These projections are designed for global coverage and reveal substantial distortions near polar regions. The level of image distortion over the region of central Canada is evident from the example in Fig. 1. It shows the image corresponding to the MODIS SIN tile (h13v03) with horizontal index 13 and vertical index 3 that covers the Hudson Bay area. Fig. 1a displays the image in the SIN projection. Fig. 1b displays the image in the Lambert Conic Conformal (LCC) projection, which is considered as a standard map projection for national scale satellite products and visualization at the Canada Centre for Remote Sensing (CCRS), Department of Natural Resources Canada. Evidently, the SIN projection is not suitable for mapping applications near polar regions, requiring reprojection into the nationally accepted geographic standard. An additional reprojection step is, therefore, almost unavoidable for many users.

A basic set of standard routines for transformation of MODIS imagery into standard geographic projections are available with the MODIS Reprojection Tool [8-10] (MRT, or MRTswath tool for swath data). Although quite useful and universal, these packages may not be properly optimized for some cases dealing with large-volume data processing. This

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increases substantially the processing time when reprojecting MODIS data over large areas, such as our region of interest (5700 km × 4800 km) covering Canada or Arctic circumpolar zone (9000 km × 9000 km) centered on the North Pole. A systematic bias of about 150 m has also been detected during testing the latest MRT swath tool version 2.1 released in January 2006. This software also produces incorrect results due to interpolation between good values and fill values for missing pixels when handling missing data blocks. These limitations justify the need for developing a new tool for reprojection of the MODIS swath data used in our project.

The capabilities of MODIS imagery with frequent (1–2 day) repeatable global coverage, rich spectral information, and hierarchy of the spatial scales are very unique. In order to preserve the image quality for any application utilizing a particular geographic projection, the number of reprojection and resampling steps must be minimized. The errors in image registration, band-to-band biases, and gridding artifacts have negative impacts on the accuracy of land parameter retrievals, change detection and trend analysis [11–13]. Ideally, the output imagery or product should be derived from the original swath-level data, because additional resampling degrades the image quality and spatial resolution. This is illustrated in Fig. 2. The left panel shows the standard 8-day composite surface reflectance Level 3 product MOD09Q1 at 250 m reprojected into LCC projection with the standard MRT tool. The panel on the right shows the surface reflectance over 10-day compositing interval produced from L1B swath data by using the reprojection routine developed in this paper. One can see the significant spatial noise on the left image, such as notched edges of the shorelines, compared to the higher quality of the right image. The difference in duration of the compositing intervals is not a factor here as it may affect only the degree of cloud contamination, but not the spatial noise shown in Fig. 2. From this comparison, it is apparent that multiple reprojections significantly degrade image quality. The spatially most accurate results have to be obtained directly from L1B (swath) data by reprojecting the imagery into the required map projection in one step.

Unlike single-detector scanning systems such as the Advanced Very High Resolution Radiometer (AVHRR) or pushbroom systems such as the European Space Agency’s Medium Resolution Imaging Spectrometer (MERIS), a single scan of MODIS consists of 1354 frames, each of them consisting of a column of 10 detectors for 1 km channels. The number of detectors is twofold and fourfold for 500 m and 250 m channels with proportional increase in the number of frames [3, 4, 7]. The spatial resolution mentioned above is a nominal spatial resolution for the nadir direction. At the largest scan angle, each nominal ‘1 km’ pixel has dimensions of approximately 4.8 km in along-scan direction and 2 km in along-track direction. Because the swath data consist of multi-detector scans, the image is composed of segments of 10, 20, and 40 lines for 1 km, 500 m, and 250 m channels,
respectively. The larger off-nadir field-of-view causes the so-called panoramic bow-tie effect, which appears as an overlap between subsequent scans and becomes stronger with larger view zenith angle. This presents a particular challenge for a processing system to convert MODIS Level 1B and Level 2 swath data into a standard map projection.

The subject of the present work is the development of a fast and accurate reprojection method for processing MODIS Level 1B and Level 2 data stored in the original swath projection (granules) to resolve the problems identified above. Mathematical solutions for the reprojection problem as a problem of finding equations relating a pair of points on input and output maps are available from the General Cartographic Transformation Package (GCTP) [14]. However, the major difficulty in implementing an efficient and accurate image reprojection package is to determine the appropriate location of samples and produce continuous output image without spatial gaps and biases. This paper presents an algorithm based on a two-dimensional gradient search for efficient reprojection of the MODIS imagery into any map projection, such as Lambert Conic Conformal (LCC), Universal Transverse Mercator (UTM), or others. The paper is structured as follows. A brief review of reprojection principles with and without interpolation is presented in Section 2. The description of the proposed method is explained in Section 3. Section 4 addresses the special case for Polar Regions, when the straightforward search can be unstable. The modification of the gradient search method for the case of overlapping MODIS image segments is discussed in Section 5. The results of testing against high-resolution Landsat imagery are discussed in Section 6. The discussion and conclusions are presented in Section 7. The Appendix section contains summary of adjustments to the equations for the transformation of coordinates for the LCC projection that increase computational efficiency of the reprojection algorithm.

II. OVERVIEW OF REPROJECTION PROCEDURE

Although the method proposed in this paper can be applied to any map projection that corresponds to continuous coordinate transformation, we consider its implementation for particular case of the LCC projection. The rationale behind the selection of the LCC projection for Canada and the choice of specific parameters are described in [15, 16]. It is known that the forward and inverse coordinate transformation for the LCC projection is characterized by continuous functions. In general, the reprojection involves the following steps (known as “forward mapping”):

1) Converting the pixel-line coordinates \((x, y)\) for each point of the source image into corresponding latitude/longitude \((\phi, \lambda)\) values;
2) Transforming the \((\phi, \lambda)\) values into coordinates of the destination geographic projection, such as easting/northing \((E, N)\);
3) Converting \((E, N)\) to the \((i, j)\) location of the pixel in the destination image and store the original pixel’s value to the found location.

Let us look at these steps from the viewpoint of accuracy and computational efficiency.

For step (1), we consider the most common case, when no analytical formulae exist to compute the latitude and longitude values \((\phi, \lambda)\) for each pixel location. In such a case, supplementary information is required, i.e. two layers of data with the latitude/longitude for each pixel of the source image. This information can be obtained by running a geolocation procedure that uses the Earth ellipsoid and terrain surface information in conjunction with spacecraft ephemerides to compute the location of each pixel. An example of such a procedure is the MODIS Earth Location Algorithm [3] or similar procedures for other sensors [17–18].

Step (2) can, in general, be performed by using analytical formulae. For the case of LCC projection, the transformation can be particularly optimized for efficient implementation on modern computers (see Appendix for details).

Step (3) appears to be the most simple, as it uses the linear transformation from \((E, N)\) to \((i, j)\) system of coordinates. This step, however, contains a serious issue related to preserving the geolocation accuracy of the output image. The problem is hidden in the implied rounding of the coordinates \((E, N)\) as real numbers into a pixel position \((i, j)\) represented by integer numbers. The straightforward rounding means selecting the nearest grid location to store the original pixel’s value. This comprises the nearest-neighbor (NN) method of reprojection (see Fig. 3).

The obvious advantage of the NN method is in preserving the original pixel values. That is why it is the only recommended method of reprojecting the discrete-level data, such as landcover maps, quality flags, etc. Although the individual pixel values are preserved, the image properties such as the histogram and statistical moments may not be precisely conserved, because of duplication (i.e. point A in Fig. 3) and/or exclusion (i.e. points B, C) of pixels depending on resolution and geometry of the output grid. By the nature of the algorithm, the NN method may also introduce significant
errors in the pixel position that can be as high as \(1/\sqrt{2}\) of the output grid spacing. Such random geolocation errors result in noticeable distortion of the land features, such as coastlines, roads, etc. [19, 20].

Unlike the discrete-level data, continuous fields, such as temperature or reflectance imagery, should be reprojected by means of interpolating methods [19, 20]. Because of interpolation, the surface features are reproduced with better geolocation accuracy. In the case of bilinear interpolation, the local extreme values of the function representing the continuous field may be smoothed, but only in the areas with a high second-order spatial derivative. In practice, the overall histogram of the image is better preserved with bilinear interpolation compared to the NN method, because the latter suffers from the random duplication and/or exclusion of pixels. Cubic spline interpolation can better reproduce extreme values than bilinear interpolation, but can also cause overshooting errors in the areas of large spatial variability or high gradients (for example, the variation of surface temperature across a coastline). The reprojection that accurately preserves image properties can be obtained by using the sinc-function and appropriate sampling intervals [20], it may, however, be ineffective computationally, resulting in impaired performance. For these reasons, we limit our implementation to the bilinear interpolation method.

During the reprojection step (3), a problem arises when one needs the correct interpolation of the reprojected data on the output grid. In the general case, the real coordinates \((E, N)\) of the reprojected data array appear in a quite irregular pattern compared to the rectangular grid of the output image, as shown on Fig. 3. A straightforward way of interpolation would be to average several of the nearest neighbors (within the circle in Fig. 3) with weighting based on their distance from the current pixel’s center or using a Kriging approach. This, however, is not only complex and computationally inefficient, but is also subjective because of the uncertainty in choosing the size of the enclosing circle.

A more natural and correct approach is an interpolation based on 4 points that are nearest in terms of the original image grid (points 1, 2, 3, and 4 in Fig. 3). In the case of bilinear interpolation, the formula for the interpolated value \(p\) of the output pixel is:

\[
p = P_1 \cdot (1 - \Delta x) \cdot (1 - \Delta y) + P_2 \cdot \Delta x \cdot (1 - \Delta y) + P_3 \cdot (1 - \Delta x) \cdot \Delta y + P_4 \cdot \Delta x \cdot \Delta y
\]

where \(P_i\) are values of the 4 original pixels; \(\Delta x\) and \(\Delta y\) are the fractional shifts (from 0.0 to 1.0) of the output point within the 4-pixel square. The \(x\) and \(y\) coordinates are measured within the original “pixel-line” grid, which means that the interpolation is, in fact, performed before the reprojection. This way of processing is more logical, because it is equivalent to building a continuous function \(f(x, y)\) based on the original array of data and sampling that function at the points corresponding to the output grid. The problem here is how to find the \((x, y)\) coordinates of those grid points.

The solution to this problem is merely the inverse sequence of the three reprojection steps described above (called ‘inverse mapping’). The routine begins with the inverse step (3) by scanning the output image pixel by pixel. The conversion of pixel’s coordinates \((i, j)\) to easting/northing \((E, N)\) is linear and is completely defined by a given scaling factor (i.e. image spatial resolution in m/pixel). The next step involves the transformation of the \((E, N)\) coordinates into corresponding latitude/longitude \((\phi, \lambda)\). In the case of the LCC projection, the direct transform \((\phi, \lambda) \rightarrow (E, N)\) has an exact analytical solution, while the inverse transform can only be obtained iteratively, in order to achieve a prescribed accuracy. However, the inverse transform can be implemented with a higher computational efficiency compared to the direct transform. An example of such an implementation is presented in the Appendix.

The final step is to find the pixel in the input image with latitude and longitude closest to the calculated values. For bilinear interpolation, besides the pixel’s position \((x, y)\), the offset of the inverse-reprojected point within the input grid is also required. It is described by the fractional shifts \((\Delta x\) and \(\Delta y)\). Having the position and the shifts, \((1)\) can be employed to calculate the interpolated pixel value and store it as the current pixel of the output image.

III. CONCURRENT GRADIENT SEARCH OF LATITUDE AND LONGITUDE

In the general case, there is no analytical transformation from the image coordinates \((x, y)\) to latitude and longitude \((\phi, \lambda)\). The only available data are the numerical arrays of \((\phi, \lambda)\) values given for each pixel. The current problem, however, is the inverse task: to find the \((x, y)\) position for the given latitude and longitude. This problem is equivalent to solving the system of equations for \(x\) and \(y\) variables:

\[
\phi(x, y) = \Phi
\]

\[
\lambda(x, y) = \Lambda
\]

where \(\Phi\) and \(\Lambda\) are the given latitude and longitude, respectively, and \(\phi\) and \(\lambda\) are some continuous functions of two variables (i.e. coordinates in the input image in terms of pixel and line).

There are no universal general methods for solving the system \((2)-(3)\). However, due to the nature of \(\phi\) and \(\lambda\) functions, an iterative approach, such as the two-dimensional Newton-Raphson method [21], can be efficiently realized. Using the Taylor series expansion one can obtain:

\[
\Delta \phi = \Phi - \phi(x_0, y_0) = \Delta x \phi'_x + \Delta y \phi'_y + ...
\]

\[
\Delta \lambda = \Lambda - \lambda(x_0, y_0) = \Delta x \lambda'_x + \Delta y \lambda'_y + ...
\]

where \(x_0\) and \(y_0\) denote the starting point of the iteration; \(\phi'_x\), \(\phi'_y\), \(\lambda'_x\), and \(\lambda'_y\) are the first partial derivatives at that point; and \((\Delta x, \Delta y)\) represents the vector pointing from the starting point to the point being sought. Since the functions \(\phi\) and \(\lambda\)
are, in fact, given numerically, their partial derivatives can be calculated by using simple differences between the corresponding neighbors.

Solution of the system of linear equations (4)–(5) yields in the first order:

\[
\Delta x = \frac{\varphi'_y \Delta \lambda - \lambda'_y \Delta \varphi}{D} \quad \text{and} \quad \Delta y = \frac{\lambda'_x \Delta \varphi - \varphi'_x \Delta \lambda}{D},
\]

where \( D = \lambda'_x \varphi'_y - \lambda'_y \varphi'_x \).

Thus, location of a point with the desired \( \Phi \) and \( \Lambda \) is predicted by the concurrent use of local gradients for both fields: latitude and longitude. At the predicted point, the new local gradients are calculated, which will then be used for the next iteration. A good convergence of this iterative method follows from the properties of \( \varphi \) and \( \lambda \) functions. They are continuous functions without local extrema, provided that the Poles are excluded and the date line (\( \lambda = 180^\circ \)) is handled properly. The stability of the algorithm requires also non-zero value for \( D \) in equations (6)–(7). To prove this let us assume the opposite, i.e. that \( D = 0 \). By rearranging equation (7) one can obtain: \( \varphi'_y / \varphi'_x = \lambda'_y / \lambda'_x \). The left side of this equation is a tangent of slope of the gradient for the latitude field, while the right side is the similar tangent for the longitude field. Equality of these tangents would mean that the two gradients lie along the same line. This implies that the two-dimensional space described by coordinates \( (\varphi, \lambda) \) degenerates into one-dimensional subspace, which is never the case for the latitude and longitude fields in any regular projection, except for the poles. This proves that \( D \neq 0 \) everywhere except the poles.

At each step of the iteration described by equations (6)–(7), the real values \( x_0 + \Delta x \) and \( y_0 + \Delta y \) are rounded towards zero in order to obtain the new \( (x_0, y_0) \) point. The iteration stops when both of the following conditions are reached:

\[
0 \leq \Delta x < 1 \quad \text{and} \quad 0 \leq \Delta y < 1
\]

(8)

This situation means that the point sought is located inside a grid square that is nearest to the last \((x_0, y_0)\) point (see Fig. 3). The pixel with the last coordinates \( x_0 \) and \( y_0 \) becomes a result of the search and moreover, the values of \( \Delta x \) and \( \Delta y \) can immediately be used as the fractional shifts for bilinear interpolation in equation (1). Therefore, reprojection using the bilinear interpolation takes nearly the same amount of time as the nearest neighbor method.

Extensive tests showed that iterations described by equations (6)–(7) converge very efficiently. On average, it takes just a few iterations to find the required pixel if the iteration begins in a corner of the image. In reality, scanning the output image pixel-by-pixel translates into a close vicinity search in the input image. Thus, the search can be started from the \((x_0, y_0)\) point saved from the previous search. In this case, the search takes just one iteration or no iterations at all, if the point sought appears within the same grid square.

If the longitude field contains the date line \( \lambda = \pm 180^\circ \), then the partial derivatives \( \lambda'_x \) and \( \lambda'_y \) will have a singularity when calculated by using simple differencing. Therefore, a special correction is required in order to ensure the continuity of functions and gradients across the date line. This can easily be achieved by adding or subtracting 360° when appropriate.

Another situation that requires special attention is the processing \( \varphi \) and \( \lambda \) fields obtained by using digital elevation maps, the so-called orthorectified data. In such a case, a local distortion of the \( \varphi \) and \( \lambda \) functions due to uneven terrain will result in a larger magnitude of the higher order partial derivatives that were neglected in equations (4)–(5). In practice, this may cause infinite looping during the iterative search between a few neighboring pixel when the conditions (8) can not be reached, meaning that the point with the requested \( \varphi \) and \( \lambda \) can not be located. A proposed solution to this problem is to allow a certain degree of extrapolation when applying equation (1). This is achieved by introducing a non-zero extrapolation distance \( \varepsilon \):

\[
-\varepsilon \leq \Delta x < 1 + \varepsilon \quad \text{and} \quad -\varepsilon \leq \Delta y < 1 + \varepsilon
\]

(9)

where typical value of \( \varepsilon \) is about 0.1. If the requested \( \varphi \) and \( \lambda \) can not be located within the allowed extrapolation, then the output pixel is marked as “missing data”. This situation happens when the requested pixel is located on a slope of the mountain and the observation geometry does not allow it to be visible by the spaceborne detector.

**IV. ANALYTICAL APPROACH IN POLAR REGIONS**

In some cases, convergence of the iterative search can be less than satisfactory, which results from neglecting the higher order partial derivatives in the Taylor series expansion (4)–(5). If those derivatives become significant, the solution (6) will contain large errors in the predicted vector \( (\Delta x, \Delta y) \) causing poor overall convergence of the algorithm. The higher order derivatives of the \( \lambda \) function become significant for swaths covering a large range of longitudes, i.e. for scenes close to (or including) the North Pole. The point of the North (or South) Pole contains a singularity where the gradients \( \lambda'_x \) and \( \lambda'_y \) may grow indefinitely and the gradient of \( \varphi \) is undefined. Therefore, the regions in the vicinity of either pole must be processed in a special way. In the region of \( -20 \text{ km} \) around the pole, a straightforward search is performed by looping through all pixels in that area. Outside that region, the gradient search is not initiated if \( \Delta x \) in equation (5) is greater than 30°. Otherwise, the first iteration step can take the search even further from the point sought. Resolution of this problem could be an analytical solution of the system (2)–(3), which would allow direct conversion of \( \varphi \) and \( \lambda \) to the image “pixel-line” coordinates \( x \) and \( y \). In fact, even an approximate solution can be satisfactory, since we only need to locate the vicinity of the point sought in order to accelerate the subsequent iterations.

The approximate solution is obtained as follows. First, the image spatial resolution along scan direction is corrected. The spatial resolution becomes lower for pixels further from the sub-satellite nadir point due to oblique observation geometry.
This is typical for all scanning mirror type systems with equal pixel time sampling intervals. For the MODIS sensor on Terra (and Aqua) platform, assuming a spherical Earth shape, the relationship between the pixel position $x$ and its corresponding coordinate $\tilde{x}$ along the scanline can be calculated as:

$$\tilde{x} = R_E \cdot \cos \left( h \cdot \sin^2 \sigma + \cos \sigma \sqrt{1 - h^2 \cdot \sin^2 \sigma} \right) \cdot \text{sign}(\sigma)$$  \hspace{1cm} (10)

where $\sigma$ is the scan angle:

$$\sigma = \left( \frac{2(x - 1)}{1353} - 1 \right) \cdot 55^\circ , \ x = 1...1354 , \ \text{and} \ h = \frac{R_E + H}{R_E}$$

where $H$ is the average orbit altitude. Equation (10) is quadratic on $\sin \sigma$ and can be uniquely inverted for calculation of the pixel position $x$ from the known coordinate $\tilde{x}$. The distance $\tilde{y}$ along the track direction depends linearly on scanline number $y$. Equation (10) is equivalent to a simpler expression $\tilde{x} = R_E \cdot \arcsin(h \sin \sigma) - \pi$, but the latter can not be analytically inverted to express $\sigma$ (and $x$) in terms of $\tilde{x}$.

To obtain a solution in the near-pole region, a polar coordinate system centered on the North Pole is introduced as shown in Fig. 4:

$$\tilde{x}_0 = \tilde{x}_p + r_0 \cdot \cos(\alpha_0)$$  \hspace{1cm} (11)

$$\tilde{y}_0 = \tilde{y}_p + r_0 \cdot \sin(\alpha_0)$$  \hspace{1cm} (12)

where $\tilde{x}_p$, $\tilde{y}_p$ denote the North Pole, $x_0, y_0$ denote the point sought, and $r_0, \alpha_0$ are polar radius and polar angle corresponding to the point sought.

The distance $r_0$ from a point to the North Pole can be found from the local latitude $\Phi$:

$$r_0 = R_E \cdot \frac{(90^\circ - \Phi)}{180^\circ} \pi$$  \hspace{1cm} (13)

where $R_E$ is the Earth’s equatorial radius. Since we need an approximate solution, the Earth’s oblateness is neglected here.

To find an approximate location of the North Pole $(\tilde{x}_p, \tilde{y}_p)$, one can use any pair of points, calculate corresponding distances $r_i$ with equation (13), and then solve the geometrical problem for the intersection of two circles. For better accuracy, the points in the pair must be far from each other, such as the opposite corners of the image. It is worth taking several pairs of points on the image boundary (such as points $p_0$ through $p_7$ shown in Fig. 4) in order to get the average result. If the North Pole is expected to be within the image, then a simplified gradient search should be employed that uses the gradient of the latitude field only, in order to find the maximum ($\phi = 90^\circ$), i.e. the exact location of the North Pole.

For conic projection with the standard parallel at latitude $\phi$, the angle $\Delta \alpha$ between two meridians $\lambda_1$ and $\lambda_2$ is calculated as

$$\Delta \alpha = (\lambda_2 - \lambda_1) \cdot \sin \phi$$  \hspace{1cm} (14)

Therefore, the angle $\alpha_0$ in equations (11)–(12) can be obtained from the following expression:

$$\alpha_0 = (\Lambda - \lambda_T) \cdot \sin \Phi - \alpha_T$$  \hspace{1cm} (15)

where $\lambda_T$ is the longitude of the true origin; $\Phi$ and $\Lambda$ are local latitude and longitude, respectively; and $\alpha_T$ is the angle of direction to the true origin in the image coordinate system. The angle $\alpha_T$ can be calculated from any point $p_i$ with known latitude $\phi_i$ and longitude $\lambda_i$ (see Fig. 4):

$$\alpha_T = \alpha_i - (\lambda_i - \lambda_T) \cdot \sin \phi_i$$  \hspace{1cm} (16)

where $\alpha_i$ is angle of the point in polar coordinates. Again, a higher accuracy can be achieved by using the average from several points taken on the image boundary.

Thus, having calculated the North Pole location $(\tilde{x}_p, \tilde{y}_p)$ and the auxiliary angle $\alpha_T$, one can use equations (11)–(15) to quickly locate the required point. Our analysis shows, that the typical error of this analytical approximation is about 5–10 km. The source of this error can be (a) non-linearity of the swath projection compared to the selected polar coordinate system (11)–(12), (b) deviation of the satellite altitude from the average value, (c) the Earth’s oblateness, and (d) variable elevation relative to the Earth ellipsoid. Even though the estimated location is determined with an uncertainty of a few kilometers; the iterative search started at that point takes normally only one step to find the exact location.

The implementation details and numerical optimization routine for the LCC projection are provided in the Appendix. The method was also expanded to reproject MODIS level 1B and other types of imagery over Canada, North America and Arctic circumpolar zone into four popular geographic projections: Plate Care (cylindrical equidistant), Lambert Conic Conformal (LCC), Universal Transverse Mercator (UTM) and Lambert Azimuthal Equal-Area (LAEA) [22]. The only difference with regards to implementation steps is in replacing the inverse and forward coordinate transformation between latitude/longitude and Easting/Northing.
V. TWO-STEP GRADIENT SEARCH FOR MODIS IMAGERY

The gradient search method described above works for reprojection of any kind of swath imagery as long as the latitude and longitude are provided for each pixel, and they are continuous functions suitable for calculation of partial spatial derivatives. The method described so far has been successfully tested for reprojection of AVHRR High-Resolution Picture Transmission (HRPT) data with 1 km nadir spatial resolution [15, 16, 23], MERIS Reduced Resolution (RR) imagery with 1.1 km nadir resolution [24], as well as the North American Regional Reanalysis data with 32 km spatial resolution [25].

The MODIS 1 km imagery in the original swath projection consists of overlapping scans, each having 10 lines and 1354 columns. This implies a discontinuity of the corresponding latitude and longitude fields for every 10 scanlines as shown in Fig. 5. It shows an example of the latitude data for several selected columns across the scan direction. The following discussion applies to the longitude data as well. The jump occurs every 10 lines for the derivative \( \varphi'_0 \), and becomes larger for columns further from the nadir. (The nadir location in Fig. 5 is near column 677). Thus, if the pixel sought corresponds to large view angles (for example, column 1), then the requested latitude \( \varphi_0 \) can often be found at more than one location (lines 1997 and 2002 in this example). This ambiguity has to be resolved so that the inappropriate points around the jump (such as lines 1999 through 2002) would not be used for the interpolation. Another problem is that the gradient search can be applied only to the points within the same image segment, since it cannot handle the local discontinuity properly.

![Fig. 5](image_url)

**Fig. 5.** The illustration of the overlap between MODIS image segments for 1 km spatial resolution pixels. The latitude data are shown for several selected columns across the scan direction. The overlap increases for columns further from nadir (which is near column 677). The averaging of each 10-pixel frame produces continuous function (shown with open circles) that can be used for the gradient search.

The proposed solution is to realize the search in two steps: inter-segment search and intra-segment search. At first, we need to calculate the average latitudes (shown with open circles in Fig. 5) for each 10-pixel frame within the scan. The resulting array of averaged data has the same number of columns with 10 times fewer lines, but it now represents a continuous field of latitudes (solid curve in Fig. 5). The array of longitudes is processed in a similar way. With continuous geolocation fields the problem is reduced to the concurrent gradient search already described in Sections 3 and 4. This first step is called the inter-segment search. It quickly locates the image segment and the column of the point with the required latitude and longitude. The fractional shift \( \Delta \varphi \) is used for the selection of the appropriate segment among the two neighbors. For example, in Fig. 5, the solid curve crosses the \( \varphi_0 \) level within the segment of lines 1991–2000, which properly resolves the ambiguity of overlapped data. Once the correct segment is located, the intra-segment search is conducted within the 10 lines of that segment. It employs the actual local gradients of latitude and longitude and finds the exact location of the pixel in terms of \( (x, y) \) coordinates and \( (\Delta x, \Delta y) \) shifts.

This procedure has to be refined for reprojection of 250 m and 500 m MODIS imagery. The geolocation information available from MODIS geolocation product MOD03/MYD03 is given for every “1 km” pixel. Thus, the 500 m imagery (MOD02HKM/MYD02HKM) and the 250 m imagery (MOD02QKM/MYD02QKM) require interpolation of latitude and longitude fields at finer grids. Since we do not use at this time the surface elevation maps at 500 m and 250 m spatial resolution, we assume that 4x4 block of 250 m and 2x2 block of 500 m pixels all have the same elevation as the 1 km pixel for the same location. In other words, the variation of surface elevation within 1 km pixel is neglected. For the majority of image scenes and MODIS data applications this assumption is reasonable and holds with good accuracy.

For 250 m and 500 m imagery, a simple linear interpolation of the latitude and longitude gradients allows the intra-segment search to perform reliably for all pixels within the same segment. However, interpolation of the data between the segment boundaries requires special attention, as demonstrated in Fig. 6. It shows an example of the interpolation problem for 250 m grid of latitude data at two selected columns across the scan direction. The original 1 km latitude grid appears to have an overlap between segments at column 360 (open circles), but no overlap at column 480 (open squares). The latter would imply interpolation along the lines connecting the open squares. However, because of the break between segments, the interpolation should actually follow the line through points A and B, meaning extrapolation of values at the edge of segments. The line connecting points B and C does not require an interpolation because of the overlap, this range of latitudes is already covered by the extrapolated data for either of the segments. If the fractional shift \( \Delta \varphi \) obtained in equations (6) corresponds to the region between points B and C (for example, the crossing point of the \( \varphi_0 \) level with the line...
connecting the nearest open squares in Fig. 6), then it has to be corrected so that the interpolation is taken between points A and B. The corrected value $\Delta y'$ is calculated as:

$$\Delta y' = \Delta y \cdot \frac{\varphi_{j+1} - \varphi_j}{\varphi_j - \varphi_{j-1}}, \quad \text{if } \Delta y < 0.5$$  \hspace{1cm} (17)

$$\Delta y' = 1 - (1 - \Delta y) \cdot \frac{\varphi_{j+1} - \varphi_j}{\varphi_{j+2} - \varphi_{j+1}}, \quad \text{if } \Delta y > 0.5$$  \hspace{1cm} (18)

where $j = 1910$ in this example.

Thus, for 500 m and 250 m grids, the fractional position $(x + \Delta x, y + \Delta y)$ obtained from the iteration process (6)–(8) has to be converted as follows:

$$x_{500m} = 2 \cdot (x + \Delta x) - 1 \quad x_{250m} = 4 \cdot (x + \Delta x) - 3$$  \hspace{1cm} (19)

$$y_{500m} = 2 \cdot (y + \Delta y) - 0.5 \quad y_{250m} = 4 \cdot (y + \Delta y) - 1.5$$  \hspace{1cm} (20)

If the $y + \Delta y$ position falls in the area of overlap between segments, then the corrected value $\Delta y'$ must be employed in equations (20).

It is important to mention that equations (19) include specific adjustments along the scan direction, which are required for correct match between the location of spatial elements and the actual samples included in a single frame of MODIS data. This issue arises from the difference in the sampling 1 km, 500 m, and 250 m pixels, as described in [3].

VI. ASSESSMENT OF MODIS REPROJECTION ACCURACY BY USING LANDSAT IMAGERY

This section summarizes all steps of the reprojection approach developed in this paper and provides evaluation of results by comparison with high-resolution imagery from Landsat. The following sequence of steps is conducted by using the routine developed in this paper for the reprojection of a MODIS MOD02/MYD02 5-minute swath granule over North America.

1) Several points at the corners and edges of the geolocation layers (latitude and longitude) are converted to the Easting and Northing in the output projection as described by equations (21)–(28) in Appendix for the LCC projection. The obtained polygon determines a boundary of the image in the output projection. (For an output projection other than LCC, the appropriate formulae are used instead.)

2) The output array of points is scanned line-by-line within the calculated boundary, and the Easting and Northing of each pixel is converted to the latitude and longitude $(\Phi, \Lambda)$ with equations (29)–(33).

3) For each $\Phi$ and $\Lambda$, the concurrent gradient search is performed in the form of iteration routine (6)–(7) in order to find the fractional (interpolated) location within the input geolocation layers. If the first iteration predicts $\Delta \lambda$ to be greater than $30^\circ$, then the analytical approximation based on equations (10)–(15) is employed in order to estimate the location of the point sought and to accelerate the subsequent iterative search.

4) In the case of MODIS swaths with overlapped segments, step 3 is used for the inter-segment search, and the intra-segment search is performed afterwards.

Steps 3–4 are repeated for each pixel of the output image in order to fill the index arrays: the integer positions $(x, y)$ and the fractional shifts $(\Delta x$ and $\Delta y)$, which will then be used for reprojection of all requested data layers.

5) For each data layer, the output image is scanned line-by-line within the boundary obtained in step 1, and the saved index arrays are used to retrieve the fractional positions within the input data layers.

6) For 250 m and 500 m image data layers, the fractional position and shifts found for the 1 km grid are converted to the higher resolution grid by using equations (17)–(20).

7) In the case of bilinear interpolation, the $\Delta x$ and $\Delta y$ are employed in equation (1) to calculate the new pixel’s value by weighting the four nearest pixels. For the nearest-neighbor method, the $\Delta x$ and $\Delta y$ are simply rounded towards the nearest pixel location.

8) The value obtained in step 7 is stored in the output image at the current location.

Implementation of the reprojection algorithm consists of two major parts: building the index arrays (steps 1–4) and reprojecting all requested data layers with help of these arrays (steps 5–8). The two time-consuming operations, the conversion $(E, N) \rightarrow (\phi, \lambda)$ and the gradient search, are performed only during steps 2–4, which greatly improves the overall performance of the algorithm.

Comparing the reprojection routine developed in this paper against the results obtained with the standard MODIS software (MRTSwath v.2.1, at the time this manuscript was prepared) produced virtually identical results in terms of pixel values of
the output reprojected image. However, there were some important differences. First, the reprojection with our algorithm performs, on average, 2–3 times faster than MRTSwath. Second, our routine provides more consistent processing of missing data frames or segments than the MRT reprojection tool. Third, some systematic biases in the pixel location for reprojected images between our results and MRTSwath output were discovered. A thorough comparison against high-resolution Landsat imagery was conducted to investigate this issue in detail.

The MODIS MOD02QKM (MYD02QKM) imagery reprojected with our algorithm and with MRTSwath tool was compared against Landsat-7 ETM+ orthorectified imagery, which was processed by the Canadian Centre for Topographic Information (CTI) to achieve georeferencing accuracy better than 30 m at a 90% level of confidence. We selected 17 MODIS Terra granules covering a region near Ottawa River, Ontario, Canada during the period of April through October, 2005. After reprojection of these granules into LCC projection with our method, a very good consistency in geolocation between the MODIS images was found, meaning that the difference (if any) in georeferencing was much smaller than the pixel size (250 m). This result is consistent with reports from the MODIS geolocation team about geolocation accuracy of MODIS/Terra imagery at the 50 m level or better [4, 26]. The reported band-to-band registration (BBR) accuracy for MODIS/Terra channels is also mostly better than 50 m [26]. These results ensure that MODIS/Terra image georeferencing is consistent between different scenes with accuracy much better than the pixel size.

To validate our reprojection method, a MODIS/Terra image (250 m/pixel, channel 2, 0.86 \( \mu \)m) taken on August 22, 2005 was compared with a Landsat-7 ETM+ image (30 m/pixel, band 4, 0.75–0.90 \( \mu \)m) taken on August 25, 2001. The comparison was conducted for the area observed from MODIS at near nadir direction, which ensured the highest spatial resolution of about 250 m per pixel. For this comparison, the MODIS imagery was reprojected to the same LCC projection as Landsat but at 120 m/pixel resolution by using the bilinear interpolation method. The two images were compared against each other by selecting 27 ground control points (GCP) and recording their corresponding positions (e.g. Easting and Northing). The distribution of the selected GCP array is shown in Fig. 7 a. Each GCP was located manually by selecting the smallest stable image features, such as lakes and/or relief features, which could be identified reliably on both images as shown in Fig. 7 b, c.

Fig. 8 presents a scatter plot of the differences in GCP location between the Landsat and MODIS/Terra imagery. The axes correspond to the Easting and Northing of the LCC projection. The case of reprojection with the gradient search method is shown with circles. For comparison, the same MODIS image was reprojected by the MRTSwath tool, with the same reprojection parameters, and similar statistics of GCP differences against the Landsat were collected. The results are shown as crosses in Fig. 8. The two big crosses indicate the location of averages and the standard deviations for each population. It is seen that the average offset between the Landsat-7 imagery and the MODIS

![Fig. 7. a) Part of the MOD02QKM Channel 2 (250 m) image (August 22, 2005, Ottawa River, Canada) reprojected to LCC projection at 120 m/pixel with bilinear interpolation. The selected GCP array is shown with crosses. b) Zoomed area of the MODIS image (shown with rectangle in image (a)). c) Corresponding area of Landsat-7 ETM+ imagery (Band 4, 0.75–0.90 \( \mu \)m, August 25, 2001) used to validate the MODIS georeferencing accuracy.](image-url)
imagery reprojected with our algorithm is negligibly small compared to the pixel size (with the standard deviation of about 50 m), which proves that the correct georeferencing is preserved during the reprojection. On the other hand, there is systematic bias of about 150 m of the image reprojected with MRTSwath software relative to the Landsat-7 image.

To evaluate the reprojection accuracy in areas of significant overlap between consecutive MODIS scans we also made a comparison of the same Landsat scene with MODIS/Terra scene taken on August 1, 2005 in the area close to the edge of MODIS swath (viewing zenith angle of 50±4°). The average bias computed for 27 identified GCPs along (across) the scan direction was found to be 12m (~27m), with standard deviations 42 m (35 m) correspondingly. These numbers confirm our assessment of the overall quality of the MODIS geolocation and our reprojection routine.

Similar procedure was repeated for MODIS/Aqua imagery. Comparison was conducted against a Landsat-7 scene for the region near Lake Winnipeg. The MODIS/Aqua image was selected with that region at near nadir view to achieve the best spatial resolution of MODIS data. The MODIS imagery was reprojected again by both methods. The results of the comparison against Landsat-7 ETM+ scene are shown in Fig. 9. In agreement with results observed for MODIS/Terra, it was found that the reprojection with the algorithm described in this paper preserves a good georeferencing accuracy of the MODIS imagery, while the result obtained with MRTSwath v.2.1 are biased by about 150 m. Additional analysis has indicated that the direction of this offset is close to the along track direction (i.e. perpendicular to the scan direction) for both cases: MODIS/Terra and MODIS/Aqua.

The band-to-band registration accuracy was reported to be quite good for all MODIS/Terra channels [26] and somewhat worse for some of the 500 m and 1 km channels of MODIS/Aqua [27]. In particular, the study of Xiong et al. [27] reported that MODIS/Aqua channel 5 (1.23–1.25 µm) has negative bias of about 300–350 m in the along-scan direction, and positive bias of about 350 m in the along-track direction, i.e. the overall bias of about 460–495 m. To provide an independent assessment of these results, we compared the geolocation accuracy of the reprojected MODIS/Aqua imagery for channel 5 against the same Landsat-7 image. The results of the comparison are presented in Fig. 10. Again, the MODIS image was reprojected with two methods: the gradient search developed in this paper and the MRTSwath. The

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Fig. 8. Validation of the geolocation accuracy of the reprojected imagery (250 m data) from MODIS/Terra. Circles show the differences in GCP location between Landsat-7 and MODIS/Terra reprojected by CCRS algorithm. Crosses indicate the differences between Landsat and the same MODIS image reprojected by MRTSwath.

Fig. 9. Reprojection accuracy for MODIS/Aqua. Circles show the differences in GCP location between Landsat-7 ETM+ (Band 4, taken on September 11, 2002) and MODIS/Aqua image (Channel 2, 250 m data taken on July 20, 2005) reprojected by CCRS algorithm. Crosses show the differences for the case of reprojection with MRTSwath.

Fig. 10. Similar to Fig. 9, but for MODIS/Aqua Channel 5 (1.23–1.25 µm, 500 m data) to evaluate the band-to-band registration accuracy.
standard deviation of the GCP locations is larger in this case because of the lower image resolution. An offset of about 500 m is evident for both methods of reprojection, which is attributed to the band-to-band registration error. This number is close to the one cited above and reported by the MODIS geolocation team [27]. The small difference (131±91 m) is again observed between the two reprojection methods, which is similar to the one shown in Figs. 8 and 9 for the case of 250 m MODIS imagery.

VII. SUMMARY AND CONCLUSIONS

The paper presents details of implementation of efficient numerical algorithm for the reprojection of satellite imagery. The method was particularly designed for the reprojection of MODIS level 1B imagery, although it also showed high efficiency in reprojecting AVHRR, MERIS satellite images and general type meteorological fields, such as North American Regional Reanalysis data sets. The method is based on a simultaneous two-dimensional search in the latitude and longitude geolocation fields by using their local gradients. Because of the MODIS whiskbroom electro-optical design, the consecutive scans overlap at larger view angles, which causes a discontinuity of the latitude/longitude fields. For that reason, the gradient search is realized in two steps: inter-segment and intra-segment search. The former uses segment-averaged gradients and the latter uses the actual local gradients within a segment. Although original MODIS geolocation fields are produced at nominal 1 km spatial grid, the method was also augmented to reproject MODIS 500 m and 250 m fields. The structure of the algorithm allows equal efficiency with the nearest-neighbor and the bilinear interpolation. A special procedure, that combines analytical and numerical schemes, is designed to reproject the imagery near the polar region, where the standard gradient search may be unstable due to singularity of the gradient fields.

The performance of the method was validated over a region of North America, located in Canada, by comparison of the reprojected MODIS/Terra and MODIS/Aqua images with georectified Landsat-7 ETM+ imagery. It was found that the imagery reprojected with the proposed method provided results that are consistent with the geolocation of Landsat with better than 50 m accuracy. This confirms that our gradient search method preserves the MODIS absolute geolocation accuracy of 50 m reported by the MODIS geolocation team [4]. Comparison of results for MODIS/Aqua channel 5 (1.24 µm) revealed a band-to-band registration error of about 500 m, which is close to the value reported in [27].

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APPENDIX: TRANSFORMATION OF COORDINATES FOR LAMBERT CONIC CONFORMAL PROJECTION

The exact formulae for transformation of latitude and longitude (φ, λ) to the projection coordinates Easting and Northing (E, N) (forward transformation) for the case of LCC projection with two standard parallels (φ1 and φ2) are given by equations (21)–(28) below

\[
m(\phi) = \frac{\cos \phi}{\sqrt{1 - \epsilon^2 \sin^2 \phi}}
\]

\[
t(\phi) = \tan\left(\frac{\pi}{4} - \frac{\phi}{2}\right) \left(1 + \epsilon \sin \phi\right)^{e/2}
\]

\[
n = \frac{\ln m(\phi_1) - \ln m(\phi_2)}{\ln t(\phi_1) - \ln t(\phi_2)}
\]

\[
F = m(\phi_1)/\left[n \cdot t(\phi_1)^n\right]
\]

\[
r(\phi) = R_E \cdot F \cdot t(\phi)^n
\]

\[
\theta = n \cdot (\lambda - \lambda_T)
\]

\[
E = E_F + r(\phi) \cdot \sin \theta
\]

\[
N = N_F + r(\phi_T) - r(\phi) \cdot \cos \theta
\]

where \(e\) and \(R_E\) are the Earth’s ellipsoid eccentricity and equatorial radius; \(\phi_T\) and \(\lambda_T\) are latitude and longitude of the true origin; \(E_F\) and \(N_F\) are Easting and Northing of the false origin. The inverse transformation required to obtain the latitude and longitude of a point from its Easting and Northing values is given by equations (29)–(33):

\[
r' = \sqrt{(E - E_F)^2 + (r(\phi_T) - (N - N_F))^2}
\]

\[
t' = \left[r'/(R_E \cdot F)^{1/n}\right]
\]

\[
\theta' = \arctan \left[\frac{E - E_F}{r(\phi_T) - (N - N_F)}\right]
\]

\[
\phi' = \frac{\pi}{2} - 2\arctan \left[t' \left(1 - \epsilon \sin \phi'\right)^{e/2}\right]
\]

\[
\lambda' = \lambda_T + \theta' / n
\]

It is seen that there is no simple analytical expression for the inverse transform for latitude φ due to the structure of
equation (32). Finding the solution for latitude $\varphi$ requires several iterations, in order to achieve the required precision. Each iteration step includes calculation of sine, exponential, and arctangent functions several times for each pixel. This makes the reprojection routine highly inefficient computationally, because modern processors evaluate the transcendental functions about 30–70 times slower than summation or multiplication functions.

Fortunately, the equation (32) can be transformed in such a way that reduces the computational load. Taking $\sin \varphi$ of both sides of equation (32), after simple trigonometric rearrangements one can obtain:

$$\sin \varphi = \frac{(1 - T^2)}{(1 + T^2)}$$

where

$$T = r' \left( \frac{1 - e \sin \varphi}{1 + e \sin \varphi} \right)^{e/2}$$

By introducing notation $S = \sin \varphi$, the couple of equations (34)–(35) is reduced to a simple rational form for $S$ and $T$. Now, the only one power function remains as the slowest operation, which greatly increases the efficiency for numerical realization.

To improve performance further, one can make use of the small value of the Earth’s eccentricity ($e \ll 1$), which allows the following expansion:

$$\frac{1 - S}{1 + S} = 1 - S e^2 + \left( \frac{1}{2} S^2 - \frac{1}{3} S^3 \right) e^4 + O(e^6)$$

Also, because in our case $T \ll 1$, equation (34) can be replaced with $S \approx (1 - T^2)^2$ in order to avoid the division operation, which is about 10 times slower than multiplication operation. The final iteration sequence is as follows:

$$T_1 = r'$$
$$S_1 = \left(1 - T_1^2\right)^2$$
$$T_2 = r' \left(1 - S_1 e^2\right)$$
$$S_2 = \frac{1 - T_2^2}{1 + T_2^2}$$
$$T_3 = r' \left(1 - S_2 e^2 + \left( \frac{S_2^2}{2} - \frac{S_2^3}{3} \right) e^4 \right)$$

$$\varphi = \frac{\pi}{2} - 2 \arctan T_3$$

This method uses only one division and one transcendent function operation during the entire iteration process. In the actual implementation, the divisions by constants can be replaced with the multiplication by the corresponding reciprocal of the constants. Our tests show that the typical relative error of this approximation is of the order of $10^{-7}$, with larger errors observed for lower latitudes. Still, in the worst case with $\varphi \approx 30^\circ$, which is close to smallest latitude values for the projection over Canada, the geolocation error does not exceed 6 meters.

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