De–striping of MODIS Optical Bands for Ice Sheet Mapping and Topography

Terry Haran and Ted Scambos, National Snow and Ice Datacenter, Cooperative Institute for Research in Environmental Sciences, University of Colorado
Mark Fahnestock, Complex Systems Research Center, Institute for the Study of Earth, Oceans, and Space, University of New Hampshire
tharan@nsidc.org
http://nsidc.org/data/tools/

Motivation: MODIS is a substantial improvement over AVHRR

Over the past 20 years, optical band data from the Advanced Very High Resolution Radiometer (AVHRR) sensor with a spatial resolution of 1100 meters and a radiometric resolution of 10 bits (1 part in 1024) have been used to map both surface features and topography in great detail over large regions of the earth's ice sheets. The Moderate Resolution Imaging Spectroradiometer (MODIS) instrument flying on the Terra and Aqua satellites has even greater potential for these applications, due to its improved spatial and radiometric resolution. Band 1 (620–670 nm = red) and band 2 (841–876 nm = near infrared) each have a spatial resolution of 250 meters per pixel and a radiometric resolution of 12 bits (1 part in 4096). Based on the success with AVHRR–based photoclinometry, MODIS should be capable of mapping ice sheet surface slopes as low as 0.0002 vs. about 0.0007 for AVHRR.

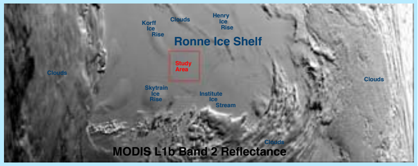
Problem: MODIS artifacts (e.g. striping) limit its usefulness

Terra MODIS Level 1b 250 meter data (MOD02QKM data) have known inter–detector variations as large as 1 per cent, leading to distinct horizontal striping in contrast–enhanced ice sheet images. This primary striping pattern appears to be due to poor calibration among the 40 detectors that constitute a single scan of MOD02QKM data. A secondary change–in–brightness pattern appears to alternate between successive 40–line scans that is probably due to mirror side effects in the double–sided MODIS scan mirror. And finally, band 1 and particularly band 2 images also show a pronounced change in brightness in every fourth pixel along each line of data for detectors 28 and 29. These three artifacts limit the usefulness of MODIS imagery over ice sheet surfaces since they constitute changes in brightness that are as large or larger than the subtle shading effects that delineate low–slope surface features such as flow lines.

Solution: Artifacts have periodicity which can aid in their removal

Although the design requirements for signal–to–noise ratios (SNRs) for bands 1 and 2 are stated to be only 128 and 201, respectively, the fact that the observed artifacts have regular patterns allows for their possible removal and the production of images having effective SNRs better than 1000. We describe here a series of empirical techniques for dampening the observed artifacts in MOD02QKM data that have proved useful in producing high quality maps and improved Digital Elevation Models (DEMs) over large regions of Antarctic ice sheets and ice shelves. The basic technique employed is to perform a series of linear regressions, first involving the 4–pixel artifact on detectors 28 and 29 (the "column" regressions), and then involving the horizontal striping (the "row"regressions). The images below demonstrate the different steps in the process for a MODIS band 2 image of a region of the Ronne Ice Shelf located between the Korff Ice Rise and the Institute Ice Stream.

Step 1: Extract swath images from HDF–EOS files



For this example we use the following Terra MODIS files acquired December 7, 2001 11:00 UTC:

```
MOD02QKM.A2001341.1100.003.2001343182214.hdf
MOD03.A2001341.1100.003.2001343161922.hdf
```

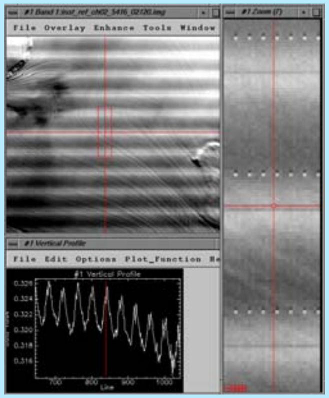
From these files we extract 53 40–line scans of 250 m band 2 data from the first file and 53 10–line scans of 1 km solar zenith data from the second file. We convert the band 2 data to reflectances (images shown at right), and we convert the solar zenith data to degrees and interpolate them to 250 m (image not shown). At this point we have two 5416 x 2120 floating–point swath images.

This entire step is performed by the MODIS Swath–to–Grid Toolbox (MS2GT) available at:

`http://nsidc.org/data/modis/ms2gt/`

The upper right image shows the entire 5416 x 2120 band 2 reflectance image at reduced resolution. The red box indicates the position and size of the 400 x 400 (approximately 100 km x 100 km) study area used in the remaining images. Note the full 5416 x 2120 image is processed, but only the 400 x 400 study area will be shown here.

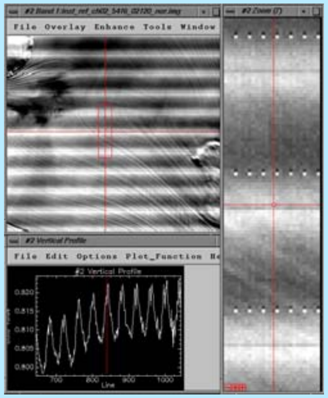
In the group of three images, the upper left image shows the study area at full resolution. The red box in this image outlines the zoomed area shown on the right. The vertical red line in each image denotes the position of a vertical profile shown in the lower left, and the horizontal red line in each image denotes the scan line corresponding to the vertical red line in the profile. This scan line has a zero–based value of 838, which corresponds to a zero–based detector number of 38 (838 mod 40).



In the zoomed image we can see that every fourth pixel for detector number 28 is anomalously dark, while every fourth pixel for detector 29 is anomalously bright. These artifacts will be corrected in step 3. In both images we can see horizontal striping. In the profile we can see that this striping has an amplitude of about +– 0.003 at a reflectance value of about 0.325, or about +–1% of the signal strength. These artifacts will be corrected in steps 4 and 5.

Step 2: Normalize with respect to solar illumination

We now divide each band 2 pixel by the cosine of the corresponding solar zenith angle pixel in order to minimize the solar illumination gradient across the image. This is done so that any remaining brightness gradients within a scan will be treated as a striping artifact which will be corrected.



These images show the result of this normalization. Note that the profile now shows a reflectance of about 0.810, and that the horizontal striping now has an amplitude of about +–0.01, still about +–1% of the signal strength.

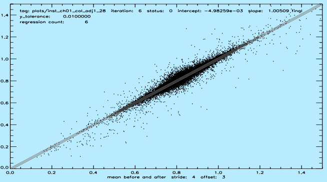
The contrast in the images shown here is a bit higher than those shown in step 1, because we are stretching each full–resolution image based on the inner 98% of the brightness histogram of the image, which now has a more compact histogram.

Steps 2 through 5 have been implemented in an IDL procedure called modis_adjust.pro, which makes calls to an IDL procedure called modis_regress.pro during steps 3 and 5. These procedures as well as an example cshell script called inst.csh and associated data files can be downloaded from:

`ftp://sidads.colorado.edu/pub/incoming/tharan/modis_adjust/`

Note that the MS2GT package mentioned in Step 1 must first be installed before attempting to run inst.csh. The use of modis_adjust.pro and modis_regress.pro will be incorporated into a future version of MS2GT, but must be run as standalone procedures at present.

Step 3: Perform column regressions to correct the "fourth pixel" artifact



In attempting to correct the "fourth pixel" artifact, we will operate on the data for detectors 28 and 29 separately.

For each detector d we assemble three vectors:

t is the "target" vector which is the collection of all the "bad" pixels for detector d.

l is the "left" vector which is the collection of all pixels immediately to the left of the target pixels.

r is the "right" vector which is the collection of al pixels immediately to the right of the target pixels.

We then form vector m which is the mean of l and r. That is:

$$m = (l + r) / 2$$

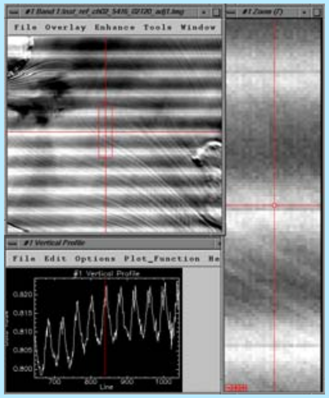
We then perform a linear least squares regression using m as the independent variable, and t as the dependent variable. The results of this regression are scalars slope s and intercept i such that:

$$t = s * m + i$$

A scatterplot of the regression for detector 28 is shown in the upper right. For the example here, the following values were obtained for the regressions for detectors 28 and 29:

SS_Detector	Col_Slope	Col_Intercept
28	-1.07514858e-02	1.00775266e+00
29	1.84437633e-02	9.89889443e-01

Note that `SS_Detector` indicates we are dealing with 40 "single–side" detectors in this step as opposed to 80 "double–side" detectors in the remaining steps.



We then apply the indicated correction to t to yield the corrected vector t':

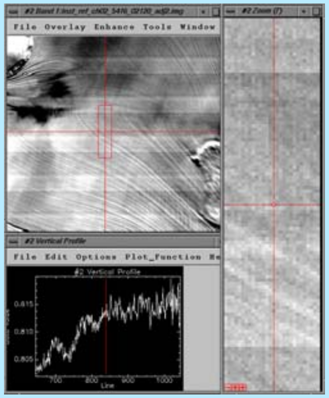
$$t' = (t - i) / s$$

Finally, we store the t' pixels back into the swath image.

Examination of the images on the lower right indicate that the "fourth pixel" artifact has indeed been corrected.

Step 4: Normalize the mean of each "double–scan" detector with respect to the mean of the entire image

We now start attempting to correct the horizontal striping artifact. From this point on, we will consider the swath image to consist of 27 "double scans" rather than the 53 "single scans"we have been using so far. Each of these double scans will consist of 80 "double–scan detectors." The reason for this is so that we can simultaneously correct for mirror–side effects as well as inter–detector calibration errors.



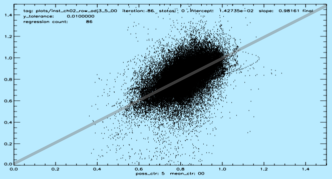
In this step, we first compute the mean reflectance over the entire image which we will call R. Then for each double–scan detector d, we construct a vector t consisting of all the pixels for d over the entire image. We then compute the mean reflectance r of vector t, and we compute a corrected vector t' such that:

$$t' = t * R / r$$

We then store t' back into the swath image, and we repeat this operation for each of the 80 double–scan detectors. This effectively normalizes the mean of each double scan detector with respect to the mean of the entire image.

The result of this operation can be seen in the images on right. Clearly the amplitude of the striping has been reduced substantially, but there is still a broad striping pattern corresponding to each double scan.

Step 5: Perform row regressions to correct residual striping



We now perform a final set of row regressions in order to minimize the striping remaining after the previous step.

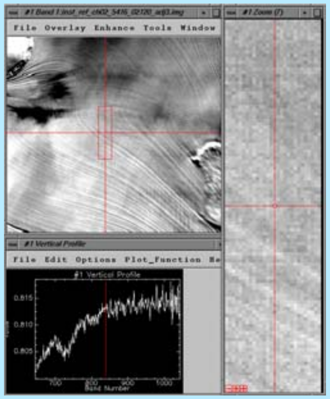
This step consists of 6 passes. In each pass, 80 linear regressions are performed, one for each double–scan detector.

In the first pass (pass 0), vectors $v(d)$ and $v(d+1)$ are constructed corresponding to each pair of adjacent double–scan detectors d and $d+1$. Then mean vector $m(d/2)$ is computed for each pair such that:

$$m(d/2) = (v(d) + v(d+1)) / 2$$

Thus for pass 0, 40 such means are computed. Each mean vector $m(d/2)$ then serves as the independent variable for two linear regressions having $v(d)$ and $v(d+1)$ as their dependent variables, yielding slopes $s(d)$ and $s(d+1)$ and intercepts $i(d)$ and $i(d+1)$. Corrected vectors $v'(d)$ and $v'(d+1)$ are then computed as follows:

$$v'(d) = (v(d) - i(d) / s(d)$$
$$v'(d+1) = (v(d+1) - i(d+1)) / s(d+1)$$



The corrected vectors $v'(d)$ and $v'(d+1)$ are then stored back into the swath image before the next pass is started. In pass 0, this procedure is repeated for each of 40 pairs of adjacent double–scan detectors.

In pass 1, the same procedure is used, except that each mean vector is computed from 4 adjacent vectors, yielding 20 such means. Pass 2 uses 8 vectors for 10 means, pass 3 uses 20 vectors for 4 means, pass 4 uses 40 vectors for 2 means, and the final pass, pass 5, uses 80 vectors for a single mean.

A scatterplot for double–scan detector 0 in pass 5 is shown in the upper right. The final resulting image is shown in the lower right. Very little residual striping can be seen in the image or in the profile. Indeed, most of the sinusoidal variation in the profile is now due to flow stripes in the ice shelf.

Optionally, the solar zenith correction applied in Step 2 can be "undone" by multiplying by the cosine of the solar zenith before the swath image is resampled into the final grid.