Obtaining Accurate Change Detection Results From High-Resolution Satellite Sensors

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***Abstract*-Multi-date acquisitions of high-resolution imaging satellites (e.g. GeoEye and WorldView), can display local changes of current economic interest. However, their large data volume precludes effective manual analysis, requiring image co-registration followed by image-to-image change detection, preferably with minimal analyst attention. We have recently developed an automatic change detection procedure that minimizes false-positives. The processing steps include: (a) Conversion of both the pre- and post- images to reflectance values (this step is of critical importance when different sensors are involved); reflectance values can be either top-of-atmosphere units or have full aerosol optical depth calibration applied using bi-directional reflectance knowledge. (b) Panchromatic band image-to-image co-registration, using an orthorectified base reference image (e.g. Digital Orthophoto Quadrangle) and a digital elevation model; this step can be improved if a stereo-pair of images have been acquired on one of the image dates. (c) Pan-sharpening of the multispectral data to assure recognition of change objects at the highest resolution. (d) Characterization of multispectral data in the post-image (i.e. the background) using unsupervised cluster analysis. (e) Band ratio selection in the post-image to separate surface materials of interest from the background. (f) Preparing a pre-to-post change image. (g) Identifying locations where change has occurred involving materials of interest.**

I. Introduction

The remote sensing community has been more concerned with the co-registration of images than the comprehensive image rectification issues of the photogrammetry community[1,2,3,4]. Terrain effects have been considered of minor impact by the remote sensing community until recently, when (a) higher resolution systems became available, (b) a greater emphasis on satellite data integration with GIS for business applications occurred, and (c) change detection and data fusion studies became more prevalent. For example, studies on the impact of mis-registration on change detection analysis have shown that a mis-registration of only one pixel can cause up to 50 percent error in some change detection applications[5], and in most applications, change detection is confused by misregistration[6,7,8,9,10,11]. It is the adverse impact of the independent variable of terrain upon pixel position knowledge that continues to demand attention despite our good understanding of satellite ephemerides (position and attitude) and sensor geometric properties. Many high-resolution sensor systems with push broom imaging designs (e.g. Ikonos, Quickbird, GeoEye and WorldView) regularly acquire off-nadir views of as much as 35 degrees, and are impacted by relief off-sets.

The development of JPL's automatic orthorectification and mosaicking system AFIDS[12,13,14,15] (**A**utomatic **F**usion of **I**mage **D**ata **S**ystem) has relied upon two key recent developments. The first is the general availability of digital elevation models (DEMs) with 1 arc second posting (nominally 30 m) for much of the world's landmasses between 60.3 degrees N/S from the Shuttle Radar Topography Mission [16]. This permits the preparation of orthorectified satellite imagery using similar techniques to those developed by the photogrammetry community for aerial photographs. The second is the preparation of orthorectified images for much of the world's landmass[17,18,95]. These two developments provide the key datasets necessary to prepare images from which subsequent high-resolution satellite imagery datasets having a pixel resolution approximating 1m can be automatically orthorectified to sub-pixel accuracy.

II. Co-registration

The recent advance in image processing capability to automatically co-register two satellite images to sub-pixel precision, using AFIDS, has made it feasible to minimize false positives associated with miss-registration and incorporate temporal changes at the pixel level into thematic classes of changes known to be associated with the materials of interest.

The AFIDS software package provides an automated process for co-registering selected satellite images from a multi-date satellite dataset having overlapping coverage of the same region. The images should not contain massive differences such as cloud, seasonal, or time-displacement variations, but, otherwise, the assumptions are non-restrictive. Given the constraints, human selection of tiepoints is *not* required, and each image will be resampled only once. Mapping and orthorectification (correction for elevation effects) of satellite imagery defines an exact projective solution because the data are not obtained from a single viewpoint (as with a framing camera), but as a continuous process along the orbital path. The basic technique we use first involves correlation and warping of raw satellite data points to the USGS Digital Orthophoto Quads (DOQ) or Controlled Image Base (CIB) (1 or 5m) databases to give an approximate mapping. The Rational Polynomial Coefficients (RPCs)[20] associated with a National Imagery Transfer Format (NITF) image provides the initial mapping from pixel coordinates to georeferenced coordinates. Digital elevation models (DEMs) then correct perspective shifts due to height and view-angle.

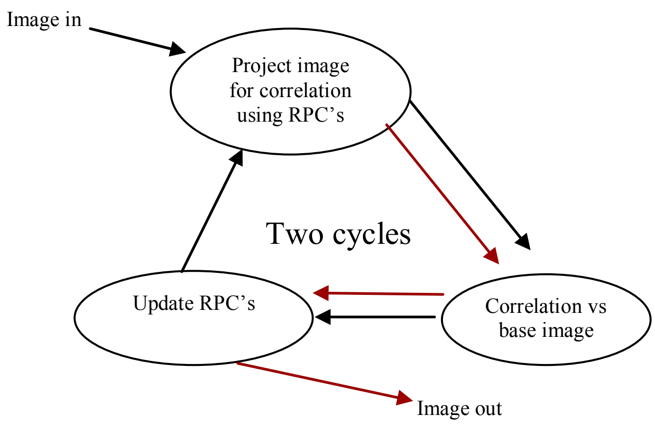

Figure 1. Use of RPC's for image registration. Two cycles are made (first) following the black arrows for one full cycle, then following the red arrows. The incoming image is projected to the coordinate system of the base (reference) image. Local correlations are performed to identify registration errors. These errors are then used to update the RPC's. Using the new intermediate RPC's, the process is repeated again leading to a set of final RPC's.

The registration process requires several sequential steps, each of which conceptually warps the dataset and involves resampling pixel values. However, to avoid degradation from multiple resampling, we represent and store each warp by an *ultra-fine grid* of tiepoints. When successive warps are required, the grids are composed mathematically into a single grid such that only one re-sampling occurs. To achieve the full benefits, all relevant programs in the processing chain must produce and/or use ultra-fine grids. The relevant programs are: (1) The warping program, (2) The elevation correction program, and (3) The 2-D FFT image correlation program[21]. In addition, another program is necessary to convert non-grids into an ultra-fine grid format. For example, the output from correlation is rarely a grid, since bland areas may not correlate well resulting in gaps. This program needs at least two modalities for converting non-grids to grids: (a) polynomial fits and (b) piece-wise linear fits. The final key to the ultra-fine grid approach is a program that can compose two initial ultra-fine grids into a single ultra-fine grid. Repeated applications of this program can then compose all of the image processing steps, each of which has its own grid, into a single grid. The *Composed Gridding* approach avoids problems that arise in the classical image processing techniques of piecewise transformation or polynomial-based geometric correction algorithms, which are known to introduce horizontal position errors in even the flattest terrain. The approach does not reduce digital elevation models to triangular irregular networks (TINs) commonly used in digital photogrammetry to lower ray-tracing computation[22]. Rather, it employs a new algorithm for image-to-image tiepoint generation that can efficiently accept up to four million points, or a 2000x2000 matrix grid. The procedure allows multiple steps to be performed by a toolbox of routines, each outputting an ultra-fine grid. While every sensor is a unique case, the toolkit of routines can address each type of systematic and erratic components associated with horizontal adjustments. Since the grids are floating point numbers, they do not contribute to a resampling type error as the composition process takes place. However, care must be taken so that the earlier transformations do not introduce errors that cannot be removed by later transformations. Our application experience has shown that sub-pixel image-to-image co-registration over entire scenes can be achieved (see Table 1).

TABLE-I

Image	Description	Pixels RMSE Master to base	Pixels RMSE Second Image to Master
QB-2	Iraq-flat plain	3.06	0.55
WV-2	Afghanistan-high relief	3.84	0.45
WV-2	Afghanistan-med relief	1.71	0.196
WV-1	Idaho-high relief-summer	1.426 to 2.508	NA
WV-1	Idaho-high relief-winter	1.784 to 3.101	NA
WV-1	Idaho-high relief-fall	2.837 to 3.643	NA

Precise co-registration of WorldView-2 images (and other high-resolution multispectral data) will generally allow for more accurate thematic classification of land-cover, crops, and changes-of-interest, as temporal and seasonal properties of the landscape can be factored in without concern for mis-classification due to mis-registration.

III. Image conditioning for change detection

In order to efficiently perform change detection, our focus has been to identify changes between two panchromatic images, and then discriminate change with multispectral data from the second date, and only for the identified change areas. Use of panchromatic imagery to delineate change allows change analysis between different sensors and satellites, hence allowing more opportunities to detect short-term changes. To accurately identify and assess changes that may have occurred between two high-resolution satellite acquisitions, we have found several useful steps that can be undertaken to assure more accurate results and limit the occurrence of false-positive recordings of change. These steps include: (a) Converting imagery to reflectance values by converting digital number counts (DNs) to top-of-atmosphere reflectance units and compensating for aerosol optical depth along the off-nadir view path. (b) When necessary, mask out areas where terrain relief is known to cause excessive mis-registration. (c) When necessary, mask out areas where clouds and cloud shadows exist, as they will falsely identify change. (d) Applying across-image normalization. See Figure 2.

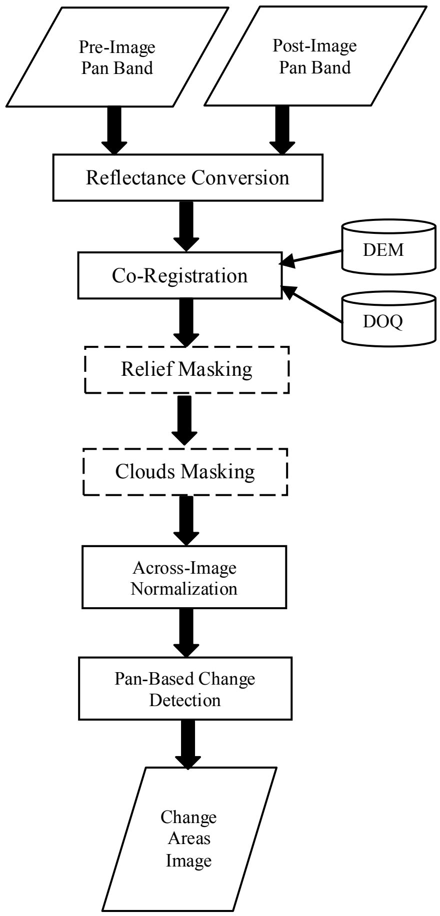

Figure 2. Steps Taken to Prepare a Change Areas Image

A. Reflectance Conversion

Converting DNs to top-of-atmosphere reflectance values is required for both multispectral and panchromatic bands when the across-track look angle is different between acquisitions by the same sensor and when different sensors are used in the change analysis processing. Top-of-atmosphere reflectance is a calibrated value that incorporates sensor dynamic ranges and bi-directional reflectance dynamics associated with the sun's position relative to satellite position and look angle to the ground. Calibrated values are available for most high-resolution sensors[23,24].

B. Relief Masking (optional)

Sometimes, areas of steep terrain cannot be effectively compensated for horizontal offset due to parallax. When the significant changes of interest are known not to occur in high relief areas, high relief areas can be masked out of consideration by applying a gradient angle threshold to elevation data[25].

C. Cloud Masking (optional)

Cloud masking is necessary when a scene is partially obscured by clouds and cloud shadows occur in otherwise clear areas of the image. Masking these areas from further consideration assures that the change detection thresholds are not unduly influenced by the reflectance values of these regions. Numerous cloud detection algorithms have been developed, but clouds in high-resolution data are most effectively detected by a combination of brightness threshold and scene texture algorithms[26].

D. Across-Image Normalization

We have found it very useful to apply a filter that normalizes between-image bands data for two separate panchromatic image acquisitions when change detection is the primary goal. This filter is applied in addition to Reflectance Conversion. Using an 11x11 filter with a center-hole of 5x5, reduces date-dependent atmospheric and view-angle variations while allowing for local signature changes associated with new materials appearing.

IV. CHANGE ANALYSIS

Change analysis steps applied to the multispectral bands of the second date is used to determine if a change signature is significant to the investigation. While a particular change detection problem may be application-dependent, change analysis of high-resolution multispectral imagery has been found to be most effective when the following steps are applied: (a) background characterization, (b) spectral differentiation, (c) pan-sharpening the multispectral data, (d) classification of change pixels, (e) applying a shape and size filter, (f) applying a materials proximity filter. Figure 3 illustrates this second group of steps involved in discriminating the type of change detected.

A. Background Characterization

Background characterization of a scene is used to help differentiate the spectral signatures of materials of interest from other materials considered as background in the second image. Unlike hyperspectral imagery, multispectral signatures of materials consist of relatively broad bands that need to be differentiated with statistical inference rather than direct template matching, and characterization of background materials in the image enhances any statistical differentiation. The process involves sub-sampling the image and computing both the dynamic range statistics for each spectral band and applying a k-means unsupervised clustering of the multispectral data[27]. Characteristically, scenes exhibit different spectral characteristics with seasons, and in the presence of clouds or haze.

B. Spectral Differentiation

Spectral Differentiation involves two procedures: (a) Use of a Normalized Difference Spectral Index (similar to NDVI[28], but applied to arbitrary bands) for spectral band-to-band signature conditioning further reduced sun angle and atmospheric effects while enhancing the spectral differentiation among materials. (b) Application of an unsupervised clustering algorithm to represent data in a finite domain and reduce dimensionality. The Genetic algorithm is used to optimize the selection of band ratios that spectrally differentiate a given material from the scene background[29,30]. Clustering is a fundamental problem in pattern recognition, and the Genetic algorithm has been found to efficiently associate the spectral band ratios most likely to identify target materials of interest from each other and the variety of background materials likely to be encountered during pattern recognition.

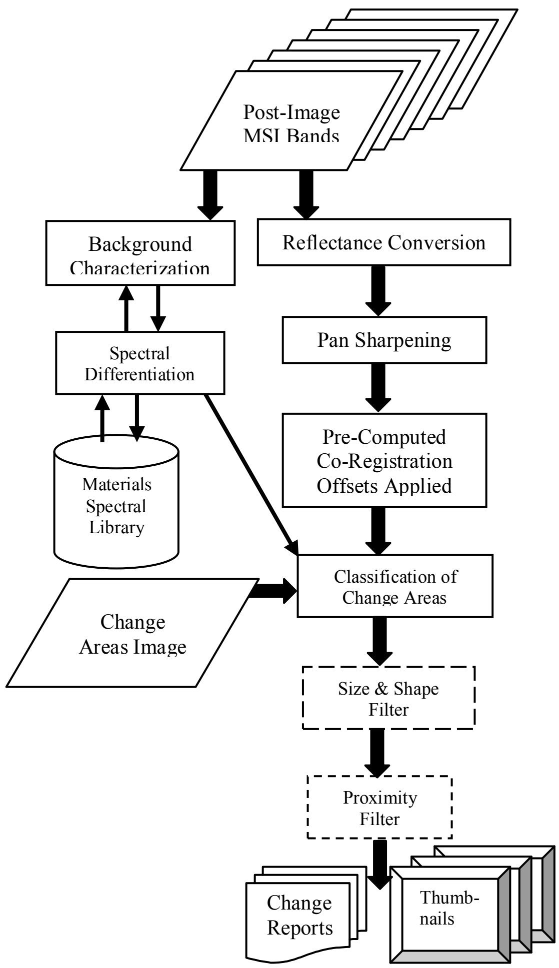

Figure 3. Steps Taken to Prepare Change Discrimination

C. Pan-Sharpening

Pan-sharpening of multispectral data reduces edge-effect spectral pixel mixing between two image dates, thereby improving the potential for recognizing "significant" changes that may result from the introduction of man-made materials. The recently developed Hypospherical Color Space pan-sharpening algorithm applied to WorldView-2 data has been found most effective[31]. Others have found in controlled experiments that sub-pixel targets with less than 25% coverage size are not detectable, even when unique targets are involved[32].

D. Classification of Change Pixels

For change pixels identified in the prepared Change Areas Image, the per-pixel application of a Bayesian statistical classifier to the multispectral bands in the Post-image selects the most-likely material from the spectral library of signatures of interest[33].

E. Size and Shape Filter (optional)

Application of a Connected Components algorithm using a size and shape threshold based on the diameter/area ratio can be used to remove isolated pixels and long thin objects related to shadows and parallax effects between scene dates[34].

F. Proximity Filter (optional)

An objects proximity analysis filter can be applied when "significant" detection requires the occurrence of two or more materials in close proximity to be judged suitable candidates[35].

V. Summary Comments

Automatic and accurate co-registration of high-resolution multispectral sensor data over time greatly enhances the analyst's ability to rapidly and objectively discriminate significant change. Also, when change detection processing is subdivided into discrete modular steps, it is possible to apply alternative support data and algorithms as conditions may require. Examples include:

1. The use of higher resolution elevation data where mis-registration due to parallax between images can falsely indicate change or abrupt features (walls or trees) create shadows.
2. The application of alternative classification algorithms developed in the science community[36].
3. Use of an alternative classifier that includes texture[37].
4. Alternative pan-sharpening algorithms[38].
5. Alternative radiometric correction procedures[39].
6. Alternative orthorectified base imagery.

Finally, the use of a polar orbiting sun-synchronous satellite data (e.g. QuickBird,WorldView, GeoEye) reduces scene-to-scene illumination differences and shadow changes between dates and improves chances to recognize actual change. Also, ensuring that image acquisitions have a small separation time (days/weeks) reduces the potential for keying on change associated with the seasons rather than man-made activity.

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References

[1] Brown, L.G. (1992), "A Survey of Image Registration Techniques," ACM Computing Surveys, vol.24, No.4, pp. 325-376, December, 1992

[2] Chalermwat, P. (1999), High Performance Automatic Image Registration for Remote Sensing, PhD Dissertation, George Mason University, Fairfax, Virginia, 84pp. 1999

[3] Fonseca, L. (1997), B.S. Manjunath, C. Kenney, "Scope and Applications of Translation Invariant Wavelets to Image Registration" in Proceedings of Image Registration Workshop (IRW97), NASA Goddard Spaceflight Center, MD, pp.13-28, November 20-21, 1997

[4] Le Moigne, J. (1997), "Towards an Intercomparison of Automated Registration Algorithms for Multiple Source Remote Sensing Data" in Proceedings of Image Registration Workshop (IRW97), NASA Goddard Space Flight Center, MD, pp. 307-316, November 20-21, 1997

[5] Townshend, J.R.G. et.al. (1992), "The Impact of Misregistration on Change Detection" IEEE Transactions on Geoscience and Remote Sensing, Vol. 30, No.5, September, 1992, pp. 1054-1060

[6] Dai,X & Khorram, (1998) "The effects of image misregistration on the accuracy of remotely sensed change detection" IEEE Transactions on Geoscience and Remote Sensing, 36:1566-1577.

[7] Stow,D. (1999) "Reducing the effects of misregistration on pixel-level change detection", International Journal of Remote Sensing, 20(12):2477-2483.

[8] Townshend,J. C. Justice, C. Gurney & J. McManus,(1992) "The impact of misregistration on change detection" IEEE Transactions on Geoscience and Remote Sensing, 30(5): 1054-1060.

[9] Verbyla, D. & S. Boles (2000), "Bias in land cover change estimates due to misregistration", International Journal of Remote Sensing, 21(18):3553-3560.

[10] Wang,H & E. Ellis, (2005) "Image misregistration error in change measurements", Photogrammetric Engineering & Remote Sensing (PERS), 44 (3) : 237-250.

[11] Smith, D.P. & S.F. Atkinson (2001), "Accuracy of Rectification Using Topographic Map versus GPS Ground Control Points" PERS, vol 67, No.5, pp 565-570

[12] N. Bryant, T. Logan, A. Zobrist (2004) "Precision Automatic Co-Registration Procedures for Spacecraft Sensors" Paper 6550 published in the ASPRS Annual Meeting Proceedings, Denver, CO, May 27, 2004

[13] N. Bryant, A. Zobrist, T. Logan, (2004)"Automatic Co-Registration of Quickbird Data for Change Detection Applications", JACIE, Reston, VA, 9 Nov. 2004

[14] N. A. Bryant, T. L. Logan, A. L. Zobrist, (2005) "Precision Automatic Co-Registration of Moderate- and High-Resolution Spacecraft Imagery" Paper presented at the ASPRS Classified Session, Bethesda MD, March, 2005.

[15] N. A. Bryant, T. L. Logan, A. L. Zobrist, (2006) "An Improved Method for Precise Automatic Co-Registration of Moderate- and High-Resolution Spacecraft Imagery" Paper published in the ASPRS Annual Meeting Proceedings, Reno, NV, May, 2006

[16] Farr, T. G., et al. (2007), The Shuttle Radar Topography Mission, Rev. Geophys., 45, RG2004, doi:10.1029/2005RG000183.

[17] Light,D.L. (1996), "The National Aerial Photography Program As A Digital Ortho Image Map Base for Geographic Information Systems", *Remote Sensing and GIS for Site Characterization,: Applications and Standards*, ASM, STP, 1279, Singhroy et.al., eds, American Society for Testing and Materials, pp. 154-159.

[18] Hacker,G and Kreuger, P.(1994),"Report on Future Mapping, Charting, and Geodesy Digital Information and Services Available form the Defense Mapping Agency", *IEEE, Proceedings of NAECON Aerospace and Electronics Conf.* p.281-288.

[19] Crampton,J (2008), "Keyhole, Google Earth, and 3D Worlds: An Interview With Avi Bar-Zeef", Cartographica, vol 43, no2, p.85-93.

[20] Grodechi,J, (2003) "Block Adjustment of High Resolution Satellite Images Described By Rational Polynomials" PERS, vol 69 p.59.

[21] Kuglin, C.D. & D.C. Hines (1975),"The Phase Correlation Image Alignment Method" Proc. Int. Conf. On Cybernetics and Society, pp.163-165

[22] Lee, P. (1991),"Comparison of Existing Methods for Building Triangular Irregular Network Models of Terrain from Gridded Digital Elevation Models", Int. Jour. Geographic Information Systems, 5(3):267-285

[23] Taylor,M. (2005)," IKONOS Radiometric Calibration and Performance After 5 Years on Orbit", Proc. Of CALCON Conf., Logan Utah 22-25 Aug, 2005. p25.

[24] Updike,T. & C. Comp, (2010) Radiometric Use of WorldView-2 Imagery, Technical Note 2010-11-01, Digital Globe.

[25] Skidmore, A.,(1989)"A Comparison of Techniques for Calculating Gradient and Aspect from a Gridded digital Elevation Model", Int, J, of Geographic Information Systems, vol.3,no.4, p. 323-334.

[26] Li,M. et al,(2004)"Automated Production of Cloud-Free and Cloud Shadow-Free Image Mosaics from Cloudy Satellite Imagery", Proc. ISPRS Congress XXXV, paper 369.

[27] Bishop,C.,(2006) Pattern Recognition and Machine Learning, Singapore, Springer. P.424-443.

[28] Tucker, C. J. (1979) "Red and photographic infrared linear combinations for monitoring vegetation." Remote Sensing of Environments 8:127-150.

[29] Aufarth,B,(2010)"Clustering by a Genetic Algorithm with Biased Mutation Operator", in IEEE Congress on Evolutionary Computation, p.1-8,July 2010

[30] Kim,P. et.al.(2011)"Genetic Algorithm and the Pendulum Problem", The Mathematical Scientist, vol 36,no.2

[31] Padwick,C. M. Deskevich, F. Pacifici, S. Smallwood, (2010) "WorldView-2 Pan-Sharpening", Proc. ASPRS Annual Conference, San Diego CA, April 26-30, 2010.

[32] Weber, K.T., & F. Chen, (2010)"Detection Thresholds for Rare, Spectrally Unique Targets within Semiarid Rangelands", PERS, 76, (11):1253-1259.

[33] Aksoy, S. et.al.,(2005)"Learning Bayesian Classifiers for Scene Classification With a Visual Grammar" IEEE Transactions on Geoscience and Remote Sensing 43(3) pp581-589.

[34] Sharir,M. (1981)"A strong connectivity algorithm and its application to data flow analysis", Computers and Mathematics with Applications, 7(1) 67-72.

[35] Berry,B. (1997),"Building Accumulation Surfaces", GeoWorld, Oct. 1997, p.26.

[36] Lu,D. & Q. Weng, (2007) "A survey of image classification methods and techniques for improving classification performance", International Journal of Remote Sensing, 28(5): 823-870.

[37] Ulfarsson,M. et al. (2003) "Data fusion and feature extraction in the wavelet domain, International Journal of Remote Sensing, 24:3933-3945.

[38] Mitani,Y. & Hamamoto,Y. (2010),"A Consideration of Pan-Sharpen Images by HSI Transformation Approach", Proc. SICE Annual Conf., Aug. 2010, p. 1283-4.

[39] Chavez,P. (1996) "Image-based atmospheric corrections: Revisited and improved", PERS, 62, (9):1025-1036.