FUSION OF KH-SERIES DECLASSIFIED SATELLITE IMAGERY AND LANDSAT MSS DATA IN SUPPORT OF URBAN LAND COVER CLASSIFICATION

Daniel Civco, Director
Anna Chabaeva, Research Assistant
Jason Parent, Academic Assistant
Center for Land use Education and Research
University of Connecticut
Storrs, CT 06269-4087
daniel.civco@uconn.edu

Manfred Ehlers, Director
Institute for Geoinformatics and Remote Sensing
University of Osnabrueck, Germany

Schlomo Angel
Woodrow Wilson School of Public & Intl Affairs
Princeton University, Princeton, NJ

ABSTRACT

In a continuation of our effort "The Dynamics of Global Urban Expansion", in which Landsat TM and ETM data were classified for the purpose of defining the "built-up area" of 120 cities around the world circa 1990 and 2000, the investigators have extended their analyses to the 1970's in order to provide a three-date series to assist in the calculation of urban growth metrics. To maintain spatial consistency among the derived datasets, Landsat MSS data were resolution-enhanced using KH-series declassified military intelligence imagery with Landsat 56-meter MSS data, by way of the Ehlers Fusion algorithm. These spatially-enhanced Landsat MSS data were classified using the same techniques as with the previously processed TM and ETM data, as reported in "The Urban Growth Management Initiative", presented at the 2005 ASPRS Annual Convention. In this "retro-analysis", two cities have been tested thus far: Kigali, Rwanda and Portland, Oregon.

These multitemporal land use data have been analyzed with our urban growth model which identifies three levels of the urban extent – the impervious surface, the urbanized area, and the urban footprint – to account for the differing degrees of open space degradation associated with the city. The model also generates metrics such as cohesion, proximity, population densities, average openness, open space contiguity, and depth which quantify spatial characteristics that are indicative of urban sprawl. We plan on expanding this time-series further, and for additional cities, with mid-decadal, gap-filled Landsat ETM data. In this paper, we discuss the procedures by which the KH-series declassified military intelligence imagery were geometrically-corrected and registered to Landsat data, the Ehlers Fusion of the KH-data with Landsat MSS, the derivation of 1970's urban land use information, and the calculation of select urban growth metrics. This paper illustrates the power of leveraging the high resolution of the military reconnaissance imagery with the multispectral information contained in the vintage Landsat MSS data in historical land use analyses.

INTRODUCTION

There is no question that the most radical change of global land cover brought about by humans is the transformation of large areas of the planet into urban land use, yet there are no reliable estimates─let alone reliable projections─of global urban land cover. There have been several efforts to estimate global urban land cover and the variation among them is substantial. These include: (1) the Digital Chart of the World (VMAP-0)−the U.S. government's digitization of navigational charts (276,400 km^2 in 1990) [Danko, 1992]; (2) the MODIS urban—fusion of nighttime lights, census, and MODIS imagery by Schneider *et al*. [2003] (726,100 km^2 in 2001), (3) the GLC2000—fusion of nighttime lights data and SPOT imagery (280,000 km^2 in 2000) [Bartholome and Belward, 2005]; and (4) the Global Urban Rural Mapping Project (GRUMP)−a GIS-based combination of ground based census data and night-time lights imagery (3,524,100 km^2 in 2000) [CIESIN, 2004]; and (5) the independent estimate by the authors and their colleagues in an earlier research project of a global built-up urban area of some 500,000 km^2 [Angel *et al*. 2005].

In an earlier study, the research team created a new universe of cities that had populations in excess of 100,000 in the year 2000 by combining the United Nations Human Settlements Programme list of 4,574 cities with an updated list of 2,884 cities provided by Vernon Henderson at Brown University into a new, comprehensive list of 3,947 cities. In this new list, most double counting was eliminated, cities for which an exact location could not be found were eliminated, and cities that were estimated to be part of larger metropolitan areas were eliminated as well. The study team considered the size of the sample necessary to derive global norms and estimates as well as to model global urban extent and expansion. It was also determined that a sample of 120 cities would be adequate for deriving statistically-significant results for the universe of cities as a whole, provided it was a stratified sample. In a stratified sample, each city in the sample represents a group of cities in the universe and is given a weight that is proportional to the share of the population of this group in the total population of the universe. Three important characteristics were used to define the strata in our sample of 120 cities: (a) the world region in which the city is located; (b) city size; and (c) the level of economic development of the country in which the city is located, measured by Gross National Income (GNI) per capita. The universe of cities was divided into nine regions, into four size categories, and into four per–capita income groups. The 120 cities studied in the World Bank and NSF-sponsored projects are listed on the project's website[1].

Global Urban Land Cover Classification

For the 120 cities studied in the preceding first phase of this research, the Landsat Thematic Mapper (TM) *circa* 1990 (T_{1990}) and Enhanced Thematic Mapper-Plus (ETM) *circa* 2000 (T_{2000}) data, both cloud-free, especially within the area of interest surrounding the cities, and on a date within two years of the respective country's population census were selected as the basis for image analysis and land cover classification [Civco e*t al*., 2005]. All Landsat data were orthographically corrected to remove geometric distortions and displacements. Each scene was geo-referenced to the Universal Transverse Mercator (UTM) projection and the WGS-84 datum. Image pixels were re-sampled to 28.5 meters. Each full-scene Landsat image was subset to just the area required to cover each city. The ISODATA clustering algorithm was used to partition the T_{1990} subset scenes into 50 spectrally separable classes. Using the Landsat data themselves, along with independent reference data when available, each of the 50 clusters was placed into one of four pre-defined cover classes: water, urban, vegetation, barren (including bare soil agriculture). Because per-pixel, spectral data-alone classification methods often encounter difficulty in discriminating between urban and barren cover types, the classification maps were carefully scrutinized to detect obvious misclassifications by comparing results with the source image, through a careful, section-by-section examination of the Landsat imagery. On-screen editing of regions of pixels obviously misclassified was performed through heads-up digitizing. The resulting land cover classifications were recoded into two classes: non-urban and urban. All the pixels, classified as urban in the T_{1990} classification, were then extracted from the T_{2000} Landsat image as it was assumed that urban development only increases with time. Then the same ISODATA algorithm along with latter class labeling and on-screen editing was performed to the portions of the T_{2000} Landsat image with results recoded into non-urban and urban classes.

Because emphasis had been placed on optimizing the classification of urban (built up) pixels, and because water often was displaced during the manual, on-screen editing process, and since water is a constraint to urban growth, this class was extracted again from the source Landsat data. A "water index" was calculated for each Landsat scene: Water Index = ($Band_1$ + $Band_2$ +$Band_3$) / ($Band_4$ + $Band_5$ + $Band_7$). The same type of Landsat T_{1990} and T_{2000} image analysis will be performed for the new set of 81 cities, resulting in two sets of maps for each city *circa* 1990 and 2000. In a future effort, similar image analysis involving the use of resolution-enhanced Landsat MSS imagery circa 1970 will be done for the set of 36 cities selected from the total universe of 201 cities, as well as possible analysis of the new Landsat ETM data *circa* 2006 – 2008. This paper presents the procedures and results of a *proof-of-concept* study in which Landsat MSS were resolution-enhanced with Declassified Satellite Imagery-2, hereafter referred to as KH, subsequently classified, and from which were extracted urban land cover metrics.

Urban Land Cover Metrics

A series of metrics has been developed to identify and measure the categories and attributes of the urban landscape (Parent *et al*., 2008). These metrics were based on land cover maps depicting urban built-up areas, water, and

[1] http://clear.uconn.edu/projects/urban_expansion/urban_expansion.html

excessive slope. For each time period, the urban built-up area was subclassified into five categories: (1) the main urban core, (2) secondary urban core(s), (3) urban fringe, (4) ribbon development, and (5) scatter development. The non-built-up area, in other words, the open space, was subdivided into four categories: urbanized open space, interior urbanized open space, peripheral open space, and core open space. New built-up areas, created during the time between T_{1990} and T_{2000} , were classified into three categories: infill, extension, and leapfrog.

The metrics used to characterize individual pixels in the Urban Landscape were all based their degree of *urbanness*, defined as the percentage of the area in a circle, 1km^2 in area, around it that was built-up. Urbanness was calculated for each pixel in the land cover map. The *urban core* consisted of all urban pixels that had urbanness values of at least 50%. The largest contiguous segment of the urban core was defined as the *main urban core*. Any remaining segments of urban core were considered *secondary urban cores*. The *urban fringe* was defined as consisting of all urban pixels that had urbanness values between 30-50%. Urban pixels with urbanness values less than 30% were classified as with either *ribbon development* or *scatter development*. Ribbon development was defined as all semi-contiguous strands of urban pixels that were less than approximately 200 meters wide. Any remaining urban pixels with urbanness values less than 30% were classified as scatter development. The *urbanized open space* consisted of open space pixels that had urbanness values greater than 50%. The *interior urbanized open space* was defined as open space pixels that were completely enclosed by the urbanized open space and urban pixels with urbanness values greater than 30%. The *peripheral open space* encompasses any open space pixels within 100 meters of the urban pixels that has not been classified as urbanized open space or interior urbanized open space. The remaining open space pixels were classified as *core open space*. The *buildable areas* were calculated for the non-core open space metrics. Open space pixels that contained water or excessive slope were considered not buildable. Excessive slopes were defined as the slope value that was greater than 99% of the slope values for the urban pixels. Slopes were calculated from Digital Elevation Models derived from the Shuttle Radar Topography Mission. New development consisted of the urban pixels that existed in the T_{2000} land cover but not the T_{1990} land cover. These pixels were assumed to have been developed between the two time periods. *Infill development* was defined as the new development that was contained in the urbanized open space of T_{1990} . New development that did not intersect the urban footprint was considered *leapfrog development*. Any remaining new development was considered *extension*. The previous study developed three definitions of the urban extent to encompass a range of perceptions of what constitutes urban land cover. The three definitions ranging from most conservative to least conservative are the (1) *built-up area*, (2) the *urbanized area*, and (3) the *urban footprint*. The built-up area consists of pixels that were classified as impervious surfaces in the land cover map. The urbanized area includes the built-up area as well as the urbanized open space and interior urbanized open space pixels. The urban footprint encompasses the urbanized area as well as pixels within$_{1990}$ 00 meters of the built-up area. Urban population densities were calculated based on each definition of the urban extent: (1) built-up area densities; (2) urbanized area densities; and (3) urban footprint densities.

Resolution Enhancement

The Landsat data used for the first phase of this on-going effort were from *circa* 1990 and 2000, and were at a resolution of 28.5 meters. The authors wished to apply the Urban Land Cover Metrics to 57-meter Landsat MSS data from the1970s. In order to maintain a reasonably consistent spatial resolution among urban land cover products, data and techniques were explored that would enable a resolution enhancement of the Landsat MSS data. KH-7 Surveillance System and the KH-9 Mapping System Declassified Satellite Imagery consists of approximately photographic 50,000 images that were taken from 1963 to1980 of various locations around the world[2]. A search of the archives[3,4] revealed that many of the study's 120 cities were covered with near-contemporaneous Landsat MSS and KH data. Two such cities– Portland, Oregon and Kigali, Rwanda–were chosen to test the resolution enhancement, classification, and urban characterization.

There are numerous methods for the enhancement of multispectral image data with panchromatic imagery of a higher resolution. Nikolakopoulos [2008] compares nine of these approaches, noting that some outperform others in preserving spectral fidelity, whereas others are superior in preserving spatial detail. An algorithm that maintains the spectral properties of the multispectral data ***and*** the spatial properties of the *sharpening* data would be ideal, but

[2] http://edc.usgs.gov/products/satellite/declass2.html
[3] http://edcsns17.cr.usgs.gov/EarthExplorer/
[4] http://glovis.usgs.gov/

there is always compromise. One approach, however, not assessed by Nikolakopoulos, is the *Ehlers Spectral Characteristics Preservation Algorithm* [Klonus and Ehlers, 2007], which is based on an HIS transform (spectral domain) coupled with an adaptive filter in the Fourier (spatial frequency) domain. The Ehlers algorithm has been shown to optimize the spectral and spatial properties of resolution-enhanced imagery, hence was chosen as the method for spatially-sharpening Landsat MSS data with higher resolution KH data.

DATA

A search of the archives was conducted for near-contemporaneous, cloud-free early- to mid-1970's Landsat MSS and KH imagery. Of the study area cities for which those criteria were met, Portland, Oregon and Kigali, Rwanda were chosen for this pilot study. Figure 1 shows the Landsat MSS and KH data for the overall study area for Portland, as well as an area of detail. Figure 2 likewise illustrates Kigali.

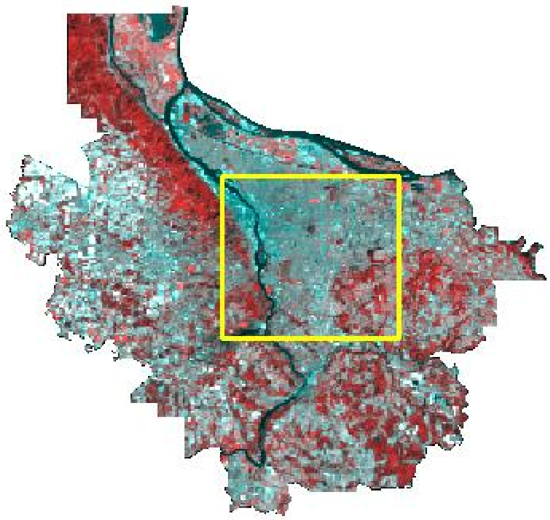


Figure 1a. Landsat MSS, July 29, 1972 of Portland, Oregon. 57 meter resolution.

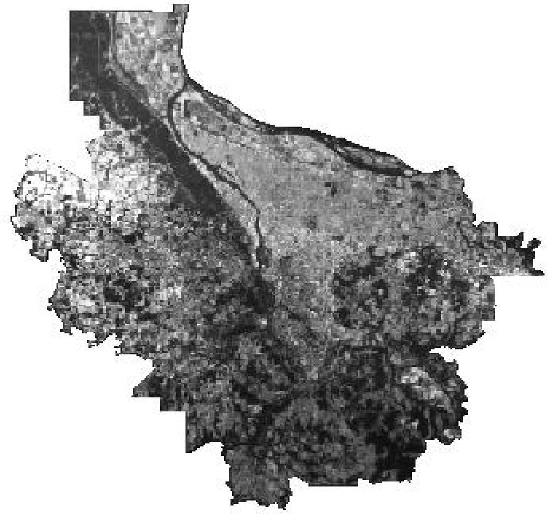


Figure 1c. KH, July 26,1973 of Portland, Oregon.1990 14.25 meter resolution.

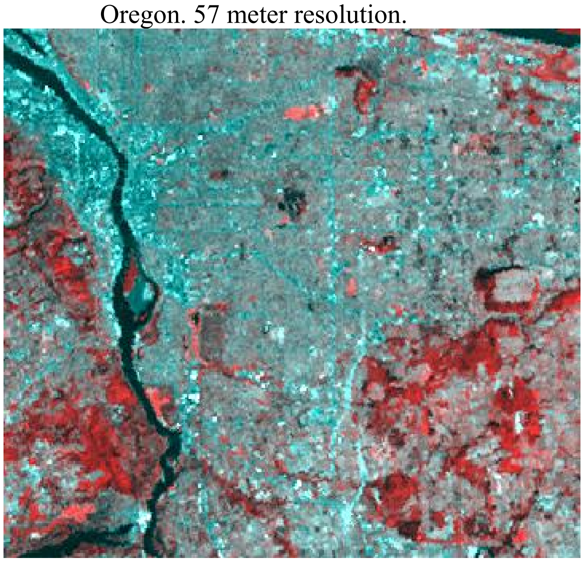


Figure 1b. Inset of Landsat MSS, July 29, 1972 of Portland, Oregon. 57 meter resolution.

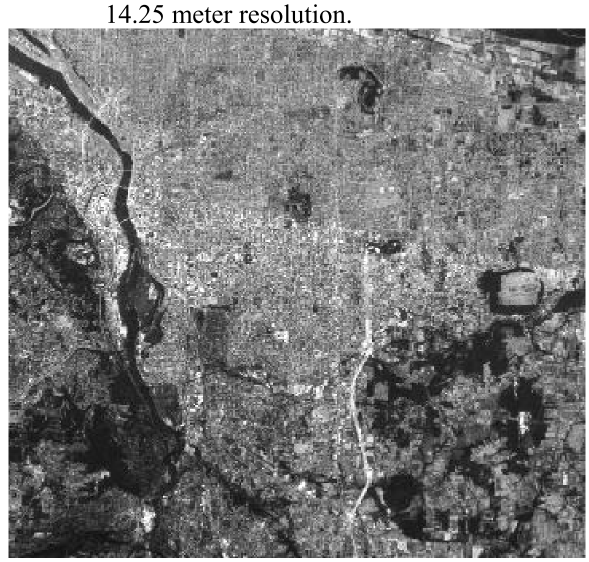


Figure 1d. Inset of KH, July 26,1973 of Portland, Oregon. 28.25 meter resolution.

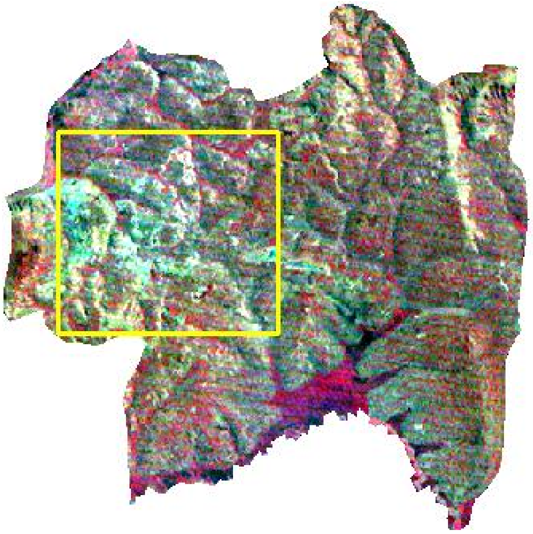


Figure 2a. Landsat MSS, August 20, 1980 of Rwanda. 57 meter resolution.

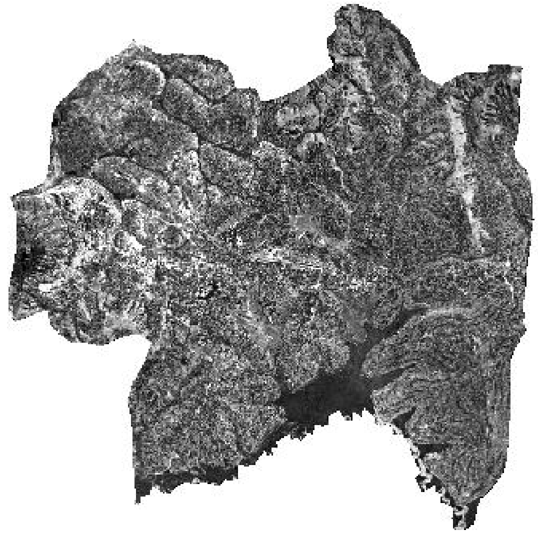


Figure 2c. KH, July 23, 19800 of Kigali, Rwanda. 14.25 meter resolution.

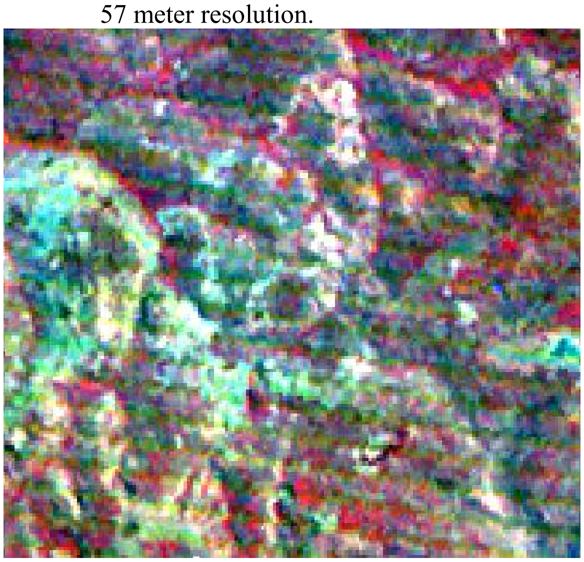


Figure 2b. Inset of Landsat MSS, August 20, 1980 of Kigali, Rwanda. 57 meter resolution.

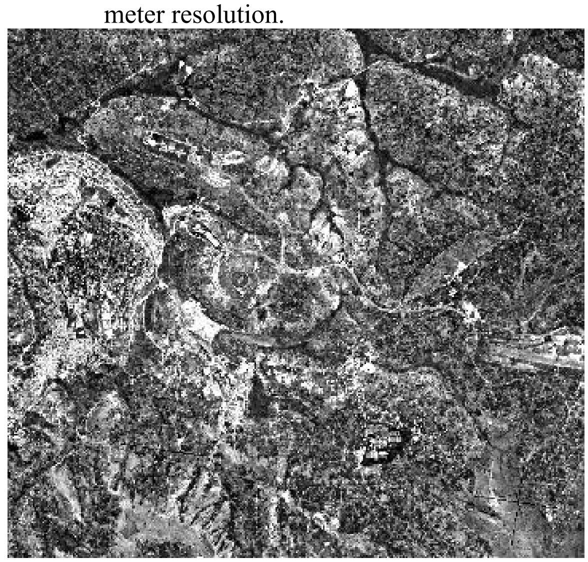


Figure 2d. Inset of KH, July 23, 1980 of Kigali, Rwanda.14.25 meter resolution.

METHODS

The methods for classifying urban land cover and for the derivation of urban land cover metrics are overviewed in the Introduction of this paper, and detailed in the literature [Angel *et al*. 2005; Civco *et a*l., 2005; Parent *et al*. 2008, 2009]. Therefore, this section will address principally the methods by which Landsat MSS data were resolution-enhanced with KH data, and the procedures for assessing the spectral and spatial properties of the resulting fused data (Figure 3).

KH data were acquired from USGS via Earth Explorer. Data were purchased as 7 micron scans of the film imagery. These data were geometrically-corrected using Landsat ETM Panchromatic (14.25 meter) imagery dated September 25, 2000 for Portland, and July 8, 1999 for Kigali. Though temporally different from the KH data (July 26, 1973 and July 23, 1980, respectively), only spatially and temporally-invariant features were selected as ground control points (GCPs). Also, since the 1970's-1980's land cover data were to be incorporated into the analyses with the already compiled *circa* land cover 1990 and 2000 data, the ETM would enable a consistent geographic reference. The KH data were corrected with a 2nd order polynomial transformation and re-sampled to 14.25 meters.

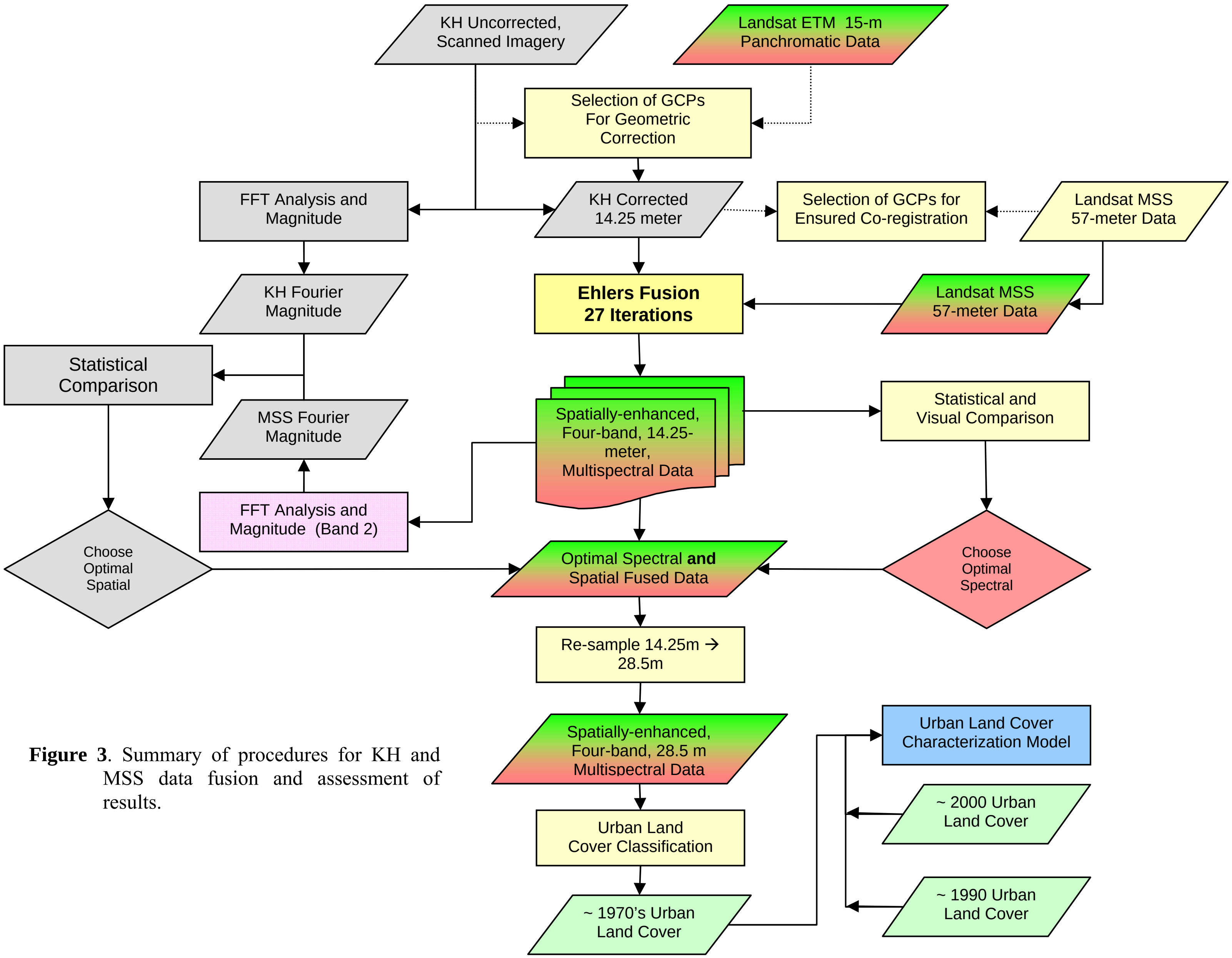


Figure 3. Summary of procedures for KH and MSS data fusion and assessment of results.

Landsat MSS data (July 29, 1972 for Portland and August 20, 1980 for Kigali) were acquired from the Global Land Cover Facility (GLCF)[5] as band-sequential GeoTIFFs. These data had already been ortho-corrected, but to ensure precise alignment with the KH data and other Landsat data being used in this project, they were corrected further, using GCPs selected from the geometrically-corrected KH data. The MSS data were corrected with a 2nd order polynomial transformation and re-sampled to 57 meters.

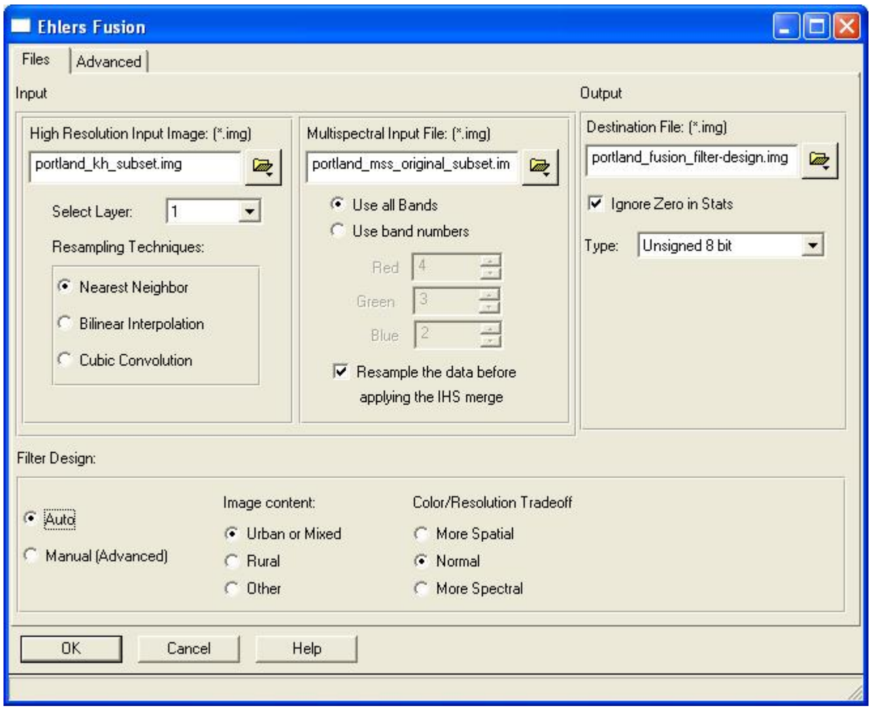


Figure 4. Dialog box for the Ehlers Spectral Characteristics Preservation Algorithm as implemented in ERDAS Imagine 9.2

The Landsat MSS data were resolution-enhanced using the *Ehlers Spectral Characteristics Preservation Algorithm* [Klonus and Ehlers, 2007], available in ERDAS[6] Imagine 9.2 and later releases. As implemented in Imagine (Figure 4), the fusion can be *fine tuned* with customized Fourier filter designs, or the user can select from a set of pre-set filters designed to maximize the preservation of spatial *versus* spectral properties – or a balance of the two – for images principally comprised by urban/mixed, rural, or other landscapes. Further, the analyst can select from among NN, BI, or CC resampling techniques, as well as which bands from the multispectral data are to be fused with the panchromatic data. For this project, the predefined filters were selected – all three 'image content' options, and all three 'color/resolution tradeoff' options, for each of the resampling methods, resulting in 27 iterations of the Ehlers algorithm. The resolution-enhanced MSS data were resampled to a 28.5 meter resolution, consistent with the Landsat TM and ETM data used for the *circa* 1990 and 2000 land cover mapping.

The resulting resolution-enhanced MSS image with the *best-perceived* results was selected for use in urban land cover classification. This was accomplished by both visual assessment (qualitative, hence subjective) and statistical (quantitative, hence more objective) methods. For the preservation of the spectral properties of the original Landsat MSS data, the resolution merged images were re-sampled to 57 meters and compared, pixel-by-pixel, with the original Landsat MSS data. Statistical measures calculated included band-by-band means and standard deviations, as well as the correlation between and the root mean square difference (RMSD) from the original and resolution-enhanced MSS data.

Whereas the principal author and his colleagues have used high pass filtering techniques to assess the quality of the spatial properties of a resolution-enhanced product relative to the original panchromatic data [Zhou *et al*., 1998], a different approach was taken in this *proof-of-concept* project. A Fast Fourier Transform (FFT) was applied to the original high-resolution KH panchromatic data, and to each of the resolution-enhanced MSS results, using $Band_{2000}$ from the latter. The rationale behind this approach is that the more alike data are in the frequency domain, the more they are alike in the spatial domain. The 'magnitude image' of the FFT was derived for the KH and the enhanced MSS (Band 2) data and compared quantitatively, especially by way of correlation and root mean square difference. The pan-sharpened data with the greatest correlation and lowest RMSD with the KH data is assumed to preserve

[5] http://glcf.umiacs.umd.edu/
[6] ERDAS, Inc., Worldwide Headquarters, 5051 Peachtree Corners Circle, Norcross, GA 30092-2500 USA

best the spatial properties of the original high resolution panchromatic (*sharpening*) data. The Landsat MSS resolution-enhanced images with a balance between spectral and spatial preserving properties were selected for urban land cover classification.

RESULTS AND DISCUSSION

Figure 5 is a graphical portrayal of the RMSD between the original and resolution-enhanced MSS data for Portland (a) and Kigali (b). Table 1 shows the minimum, maximum, and average RMSD values, by band, for the two study sites. Clearly, the fusion for the Kigali Landsat MSS data yielded better results, in terms of mimicking the original MSS values, than for Portland. This is likely due to, among other factors, the greater landscape hence spectral – variability in the Portland data (Table 2). The slightly poorer spectral results for the Portland MSS data were contributed to especially by Band 4 {0.8 to 1.1 μm}, which was consistently worse than the other three bands.

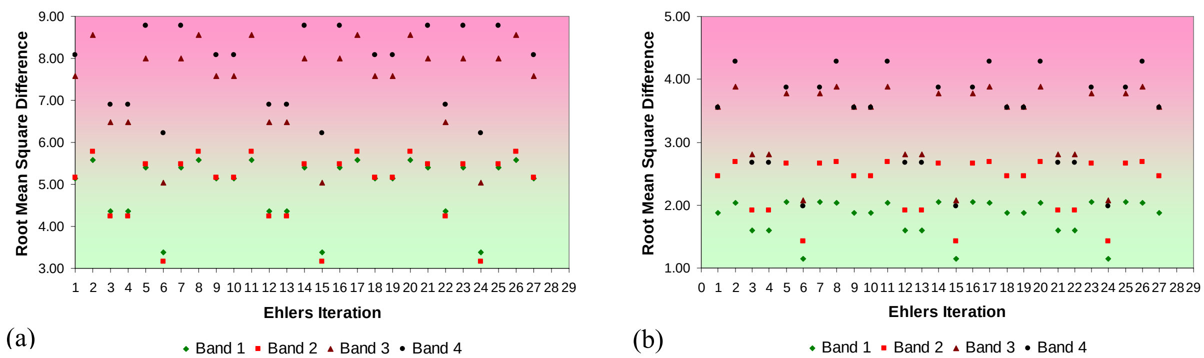


Figure 5. Root mean square difference (RMSD) between original and resolution-enhanced Landsat MSS data for each of the 27 iterations of the Ehlers technique, using all three 'image content' options, all three 'color/resolution tradeoff' options, all three resampling methods, for (a) Portland MSS, and (b) Kigali MSS.

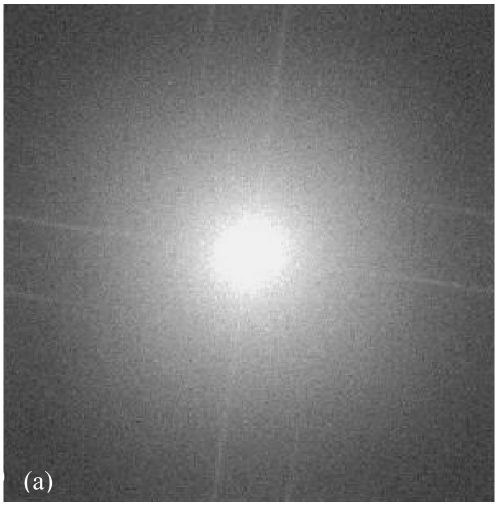
Table 1. Minimum, maximum, and average root mean square difference from all 27 iterations of the Ehlers technique

	Portland				Kigali			
	Band1	Band 2	Band 3	Band 4	Band1	Band 2	Band 3	Band 4
Minimum	3.38	3.16	5.03	6.22	1.15	1.43	2.07	1.98
Average	4.97	4.99	7.42	8.35	1.81	2.32	3.35	3.41
Maximum	5.59	5.78	8.55	10.36	2.05	2.69	3.88	4.28

Table 2. Mean and standard deviation of the original Landsat MSS data

	Portland				Kigali			
	Band1	Band 2	Band 3	Band 4	Band1	Band 2	Band 3	Band 4
Mean	27.22	24.26	45.29	44.09	21.46	24.83	38.88	40.19
Std Dev	5.84	10.41	9.96	11.39	2.23	4.21	4.82	5.64

As an example, Figure 6 shows the magnitude images for the FFT of the Kigali KH data and $Band_{2000}$ from the resolution-enhanced MSS data, using a combination of the Ehlers algorithm options of maximizing spatial properties, for a mixed landscape, using bilinear interpolation resampling. Correlation coefficients between the KH and the MSS FFT frequency for all magnitude images for the 27 iterations ranged from 0.56 to 0.81, with a mean of 0.74, for the Portland data, and from 0.57 to 0.83, with a mean of 0.77, for Kigali. In general, the higher correlations were achieved for those iterations of the Ehlers algorithm in which spatial resolution was to be preserved over spectral, confirming the intent and operation of the algorithm, at least for these test data.



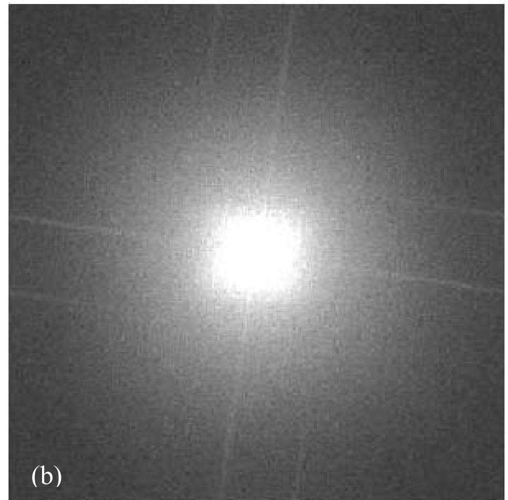
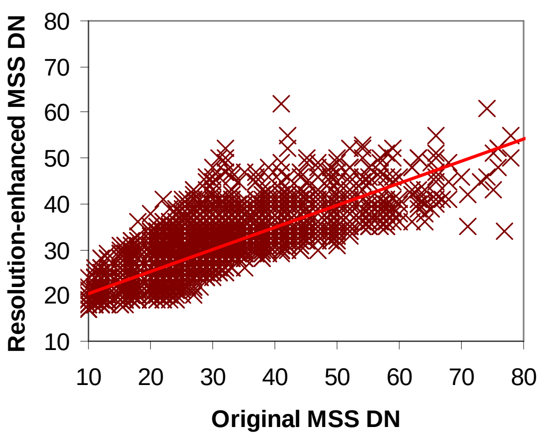


Figure 6. FFT magnitude image for Kigali (a) KH data and (b) Band 2, resolution-enhanced MSS data. $R^2 = 0.82$.

As stated earlier, MSS resolution-enhanced images to be used in urban land cover classification were chosen on the basis of a balance between spectral and spatial preserving properties. This selection was made by inspecting the comparative statistics (RMSD, correlation), by assessing R-G-B displays of the enhanced MSS data, and by examining bi-variate plots of the spectral *versus* spatial RMSD. Based on these assessment tools, a scene for each Portland and Kigali was selected. Figure 7 is a bivariate plot of the original and resolution-enhanced MSS Band_{2000} Figure 8 shows the resolution-enhanced (28.5 m) MSS data used for further analysis.



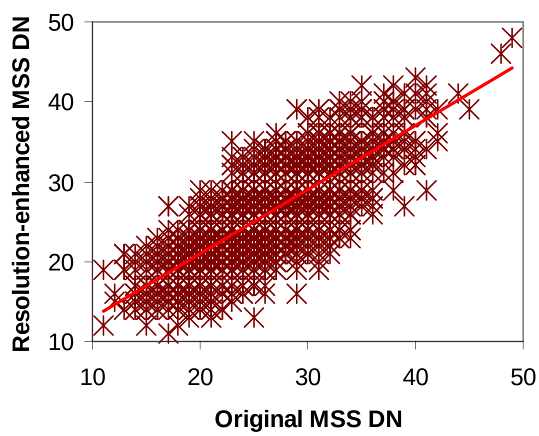


Figure 7. Biviariate plot of Band 2 digital numbers for resolution-enhanced versus original MSS data for (a) Portland and (b) Kigali.

The data illustrated in Figure 8 were subjected to the urban land cover classification and characterization procedures developed by these authors and described elsewhere in this paper and in the literature [Angel *et al*. 2005; Civco *et al*., 2005; Parent *et al*., 2008; Parent *et al*., 2009]. Figure 9 shows the urban land cover data derived for Portland and Kigali using the resolution-enhanced Landsat MSS data, as well as for the $\textit{circa}_{1990}$ 990 and 2000 urban land cover created in earlier phases of this project. Figure 10 shows some of the urban growth metrics derived from these 1970's decadal Landsat MSS data, and Figure 11 shows some of the urban growth metrics between the first two time periods of this tri-decadal urban land cover dataset. Tables 3 and 4 present summary data for some of the urban land cover metrics for both study cities. Discussion of the results of metrics analysis is beyond the scope of this paper and will be addressed elsewhere in the published literature for all 120 cities in our database.

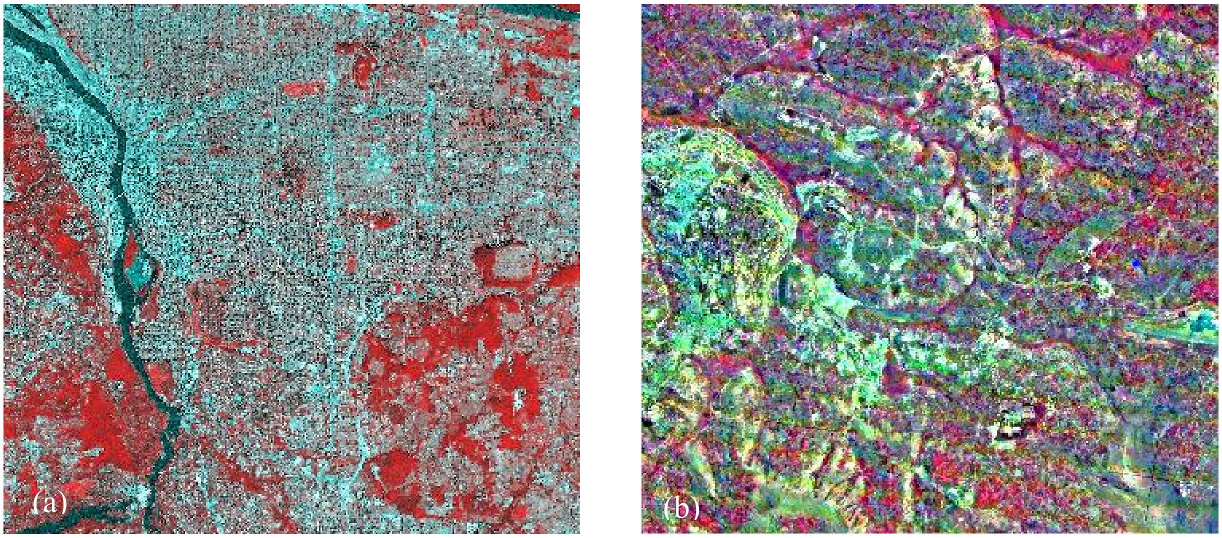


Figure 8. Resolution-enhanced Landsat MSS data for (a) Portland, using a rural landscape model, spatial criterion, and bilinear interpolation for the Ehlers algorithm, and (b) Kigali, using a mixed landscape model, spatial criterion, and bilinear interpolation. The average four-band spectral RMSD between the original and the resolution-enhanced data was 6.92 for Portland, and 3.22 for Kigali. The correlation between the FFT magnitude images (spatial measure) was 0.81 and 0.82, respectively for Portland and Kigali.

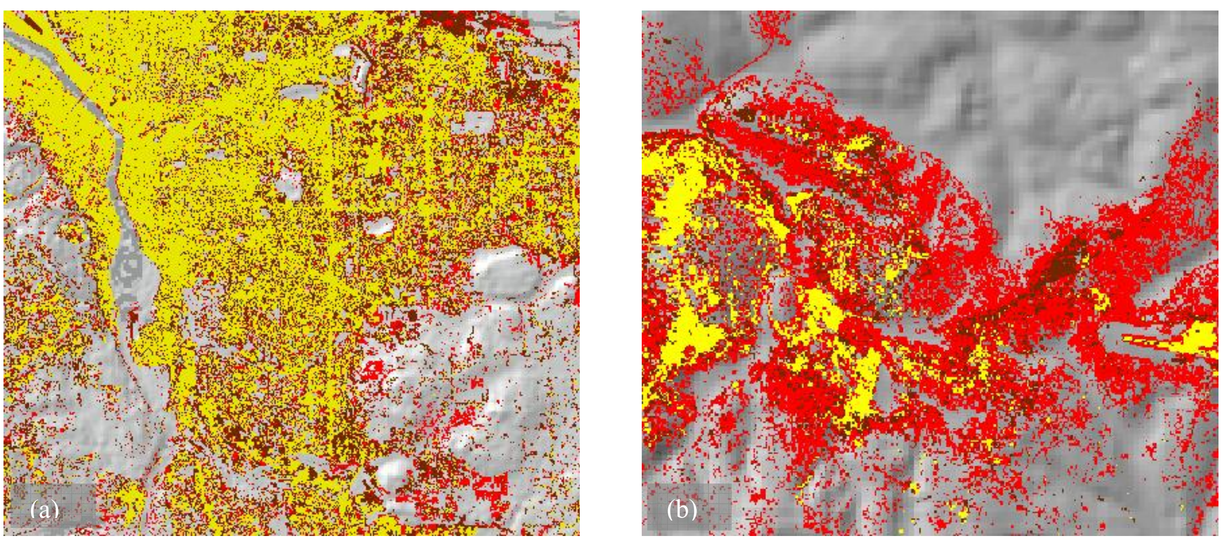


Figure 9. Urban land cover for$_{1990}$ 970’s decadal resolution-enhanced MSS data (yellow),$_{1990}$ 990’s decadal Landsat TM data (brown), and 2000’s Landsat ETM data (red), all at 28.5 meter resolution, for (a) Portland and (b) Kigali.

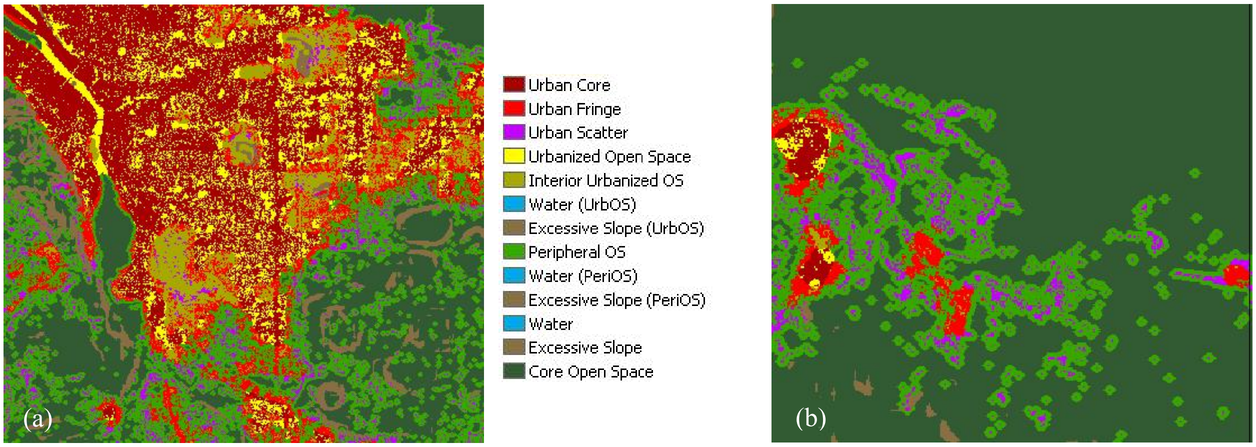


Figure 10. Urban land cover characterization for (a) Portland and (b) Kigali based on resolution enhanced Landsat MSS data.

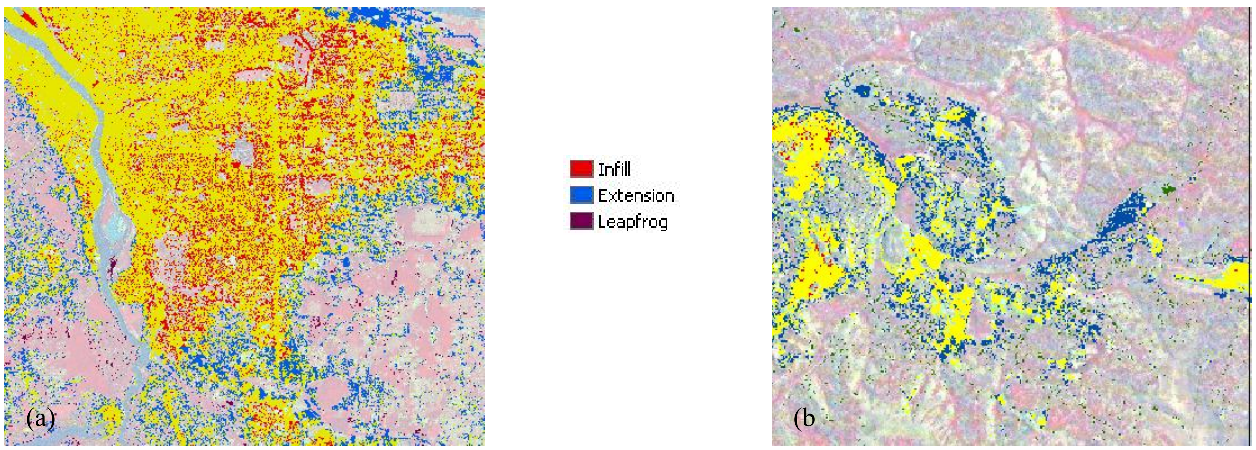


Figure 11. Urban growth characterization as either infill, extension, or leapfrog development between T_{1990} and T_{2000} of the three-decade dataset for (a) Portland, 1973 to 1990, and (b) Kigali, 1980 to1990. Urban land cover extant in $T_{\sim1970\text{-}80}$ is shown as yellow.

Table 3. Summary areas (hectares) for some key urban characterization metrics for three dates of urban land cover for Portland and Kigali.

		Portland			Kigali	
Year	**1972**	**1990**	**2000**	**1980**	**1984**	**1999**
Urban Core	12,187	35,453	55,405	99	271	3,112
Urban Fringe	6,896	12,425	11,760	220	577	637
Urban Scatter	6,853	11,624	12,814	393	708	823
Urbanized Open Space	5,284	12,387	17,034	34	126	1,015
Interior Urbanized OS	3,237	6,725	6,576	23	85	128

Table 4. Summary areas (hectares) for some key urban growth metrics.

	Portland		Kigali	
	1972 to 1990	**1990 to 2000**	**1980 to 1984**	**1984 to 1999**
Infill	2,100	6,064	18	149
Extension	21,736	12,191	586	2,525
Leapfrog	7,559	2,222	239	335

CONCLUSIONS

The authors are confident that, if conditions are ideal and criteria are met, the enhancement of coarse resolution Landsat MSS data with high resolution KH satellite data can be an effective approach to deriving vintage (1970's) Landsat data with resolution consistent with more recent Landsat TM and ETM data. Criteria, of course, are that the data are near-contemporaneous (in both season and year), cloud-free (or nearly so), geometrically-coregistered as closely as possible, among other considerations. The research team will continue to process *circa* 1970's Landsat MSS data as described in this paper to augment their global urban land cover database, and will extend their analyses to include mid-decadal 2000's (*circa* 2005-08) Landsat ETM data.

ACKNOWLEDGMENTS

The research reported in this paper was supported in part by the National Aeronautics and Space Administration under the project *Incorporating NASA's Applied Sciences Data and Technologies into Local Government Decision Support in the National Application Areas of Coastal Management, Water Management, Ecologic Forecasting and Invasive Species*. [CLEAR Publication Number 080912.1]

REFERENCES

Angel, S., S.C. Sheppard, D. L. Civco, R. Buckley, A. Chabaeva, L. Gitlin, A.Kraley, J. Parent, and M. Perlin. 2005. The Dynamics of Global Urban Expansion. Project Completion Report. Transport and Urban Development Department, The World Bank, NY. 200 p.

Angel, S., J.P. Parent, and D.L. Civco 2007. Urban sprawl metrics: an analysis of global urban expansion using GIS. Proc. 2007 ASPRS Annual Convention, Tampa, FL.$_{1990}$ 2 p.

Bartholome E., and A.S. Belward. 2005. GLC2000: a new approach to global land cover mapping from Earth observation data. International Journal of Remote Sensing 26(9):1959-1977.

Center for International Earth Science Information Network (CIESIN), Columbia University; International Food Policy Research Institute (IFPRI); The World Bank; and Centro Internacional de Agricultura Tropical (CIAT). 2004. Global Rural-Urban Mapping Project (GRUMP), Alpha Version: Urban Extents. Palisades, NY: Socioeconomic Data and Applications Center (SEDAC), Columbia University. Available at http://sedac.ciesin.columbia.edu/gpw.

Civco, D.L., A. Chabaeva, S. Angel, S. Sheppard. 2005. The Urban Growth Management Initiative - Confronting the Expected Doubling of the Size in the Developing Countries in the Next Thirty Years - Methods and preliminary results. Proc. 2005 ASPRS Annual Convention, Baltimore, MD.$_{1990}$ 2 p.

Danko, D.M. 1992. The Digital Chart of the World Project. Photogrammetric Engineering and Remote Sensing 58:(8):1125-1128.

Klonus S. and M. Ehlers. 2007. Image fusion using the Ehlers spectral characteristics preservation algorithm. GIScience & Remote Sensing 44(2):1548-1603.

Nikolakopoulos, K. G. 2008. Comparison of nine fusion techniques for very high resolution data. Photogrammetric Engineering & Remote Sensing 75(5):647-659.

Parent, J., D.L. Civco, and S. Angel. 2008. An Analysis of Global Urban Sprawl. Proc. 2008 ESRI User Group Conference, San Diego, CA.

Parent, J. Angel, S. and D.L. Civco. 2009. Urban sprawl metrics: an analysis of global urban expansion. Photogrammetric Engineering & Remote Sensing June 2009 Special Issue on "Spatial Change Analysis" (Submitted May 2008)

Schneider A, M.A. Friedl, D.K. Mciver, C.E. Woodcock CE. 2003. Mapping urban areas by fusing multiple sources of coarse resolution remotely sensed data. Photogrammetric Engineering and Remote Sensing 69(12):1377-1386.

Zhou, J., D.L. Civco, and J.A. Silander. 1998. A wavelet transform method to merge Landsat TM and SPOT panchromatic data. International Journal of Remote Sensing 19(4):743–757.