COMPARISON OF METHODOLOGIES TO DERIVE A NORMALIZED DIFFERENCE THERMAL INDEX (NDTI) FROM ATLAS IMAGERY

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ABSTRACT

A major challenge of classifying urban infrastructure using remote sensing is distinguishing pavements from roofs. We propose that due to their differing thermal masses, these elements will heat and cool differently, and therefore their Thermal/IR signatures will differ. We used spectral data gathered by NASA's Advanced Thermal and Land Applications Sensor (ATLAS) instrument to test this concept. ATLAS is a 15-channel multispectral scanner that incorporates the bands of the traditional Thematic Mapper instrument with additional bands in the middle reflective infrared and thermal infrared (TIR, bands 10-15). The TIR capability permits the accurate measurement of thermal response for different land characteristics. Image processing techniques were applied to all bands from the imagery to determine the relative viability of differentiating urban infrastructure. This research tests a new indicator, the Normalized Difference Thermal Index (NDTI). The NDTI is based on techniques that are successfully implemented in other image processing application areas. If materials have different spectral responses, then ratioing the significantly distinguishing bands and normalizing those values to a standardized range will provide a sensitive and comparable test of thermal character. It was found that two of all the possible NDTI combinations provided the best results for both pavements and rooftops.

INTRODUCTION

Remote sensing is the collection of data and information about an object from a distance. Remote sensing has been used for everything from city planning to archaeological investigation. The collection methods range from land based data acquisition to sensors placed on helicopters, planes, and satellites. There are many sensor technologies used for remote sensing, but the majority utilize the electromagnetic spectrum. The emergence of new sensors with increased spatial and spectral resolution holds the potential to allow greater feature delineation. Older sensor platforms, such as the original Landsat Thematic Mapper (TM) satellite, had spatial resolutions of 30 m per smallest picture element (pixel), which may not provide enough detailed information for urban applications. Newer platforms being tested, such as the airborne Advanced Thermal and Land Applications Sensor (ATLAS), provide spatial resolutions of 10 m per pixel. The increased spatial resolution is crucial for distinguishing between buildings and other characteristics of the urban landscape. The increase in sensor spectral resolution has encouraged material identification. Many materials have a distinctive spectrum in the hyperspectral region. However, using even the most advanced hyperspectral remote sensing techniques it is still not possible to distinguish clearly between pavements and roofs (Herold 2004). Their hyperspectral spectra are similar because they are made of similar materials. However, because the material application is different, we hypothesized that the thermal emissions of pavements and rooftops will vary throughout the day due to their differing construction techniques and thermal masses. For example, the thermal emissions of an asphalt parking lot should vary slowly throughout the day because the earth is a large thermal mass that moderates the solar heating of the pavement. Conversely, an asphalt roof should have greater temperature swings because it is insulated from a thermal sink. This differential thermal inertia is the theoretical basis upon which we propose and test the efficacy of the NDTI concept in distinguishing pavements from roofs (Figure 1).

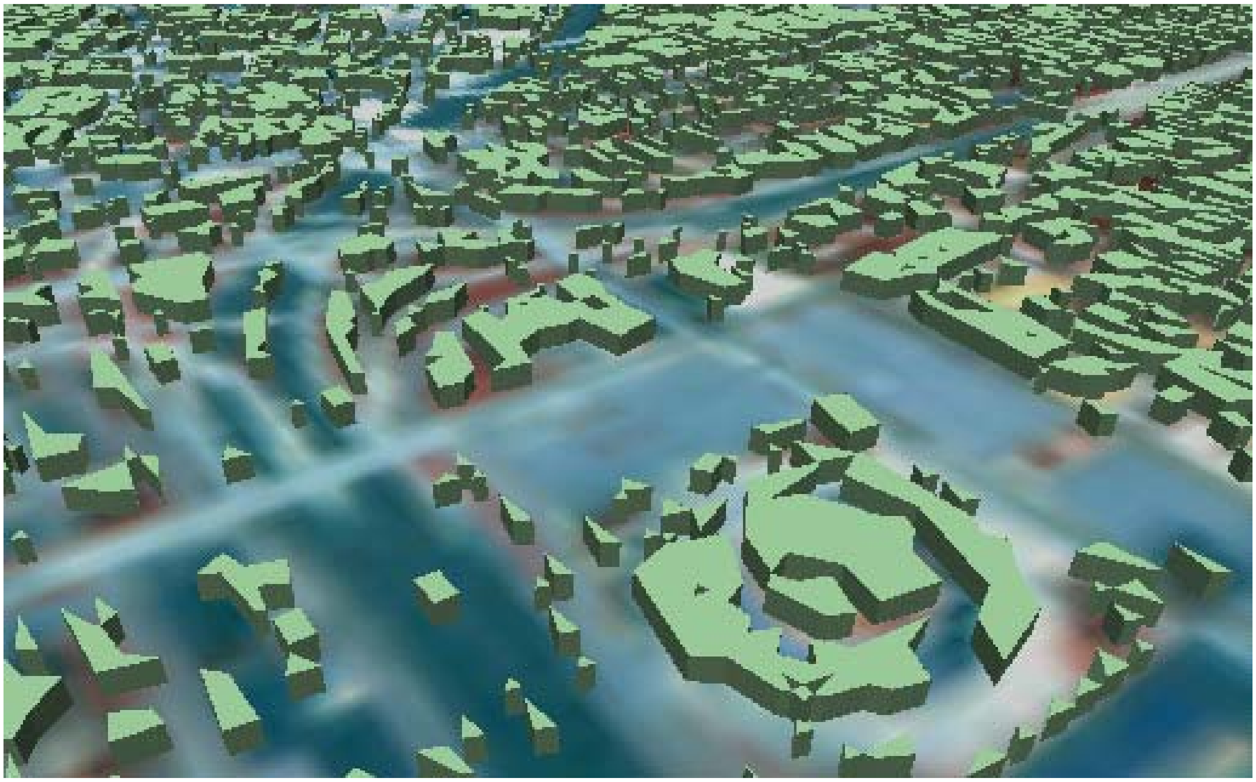

Figure 1. In this 3-D representation of the Atlanta, Georgia, study area, as determined from the NDTI , the circular structural form of Turner Stadium is clearly seen (lower center-right). The NDTI also well defines the parking lot and the linear Abernathy Boulevard to the north of the stadium, and Capitol Avenue to its east. The intersection of Interstate 75 (lower left) and the curvilinear Interstate 20 (across the upper third) are easily seen. (Note that this 3-D image is intended only to make the roofs stand out and does not represent actual building height.)

BACKGROUND

In our study we used data taken by the ATLAS sensor system on board a NASA Stennis LearJet over an area centered on Atlanta, Geargia, in May 1997 (Figure 2). The data were collected at approximately 5032 meters above mean terrain, resulting in a spatial resolution of approximately 10 m per pixel. Spectral bands 1 to 7 are similar to those on the Landsat TM satellite.

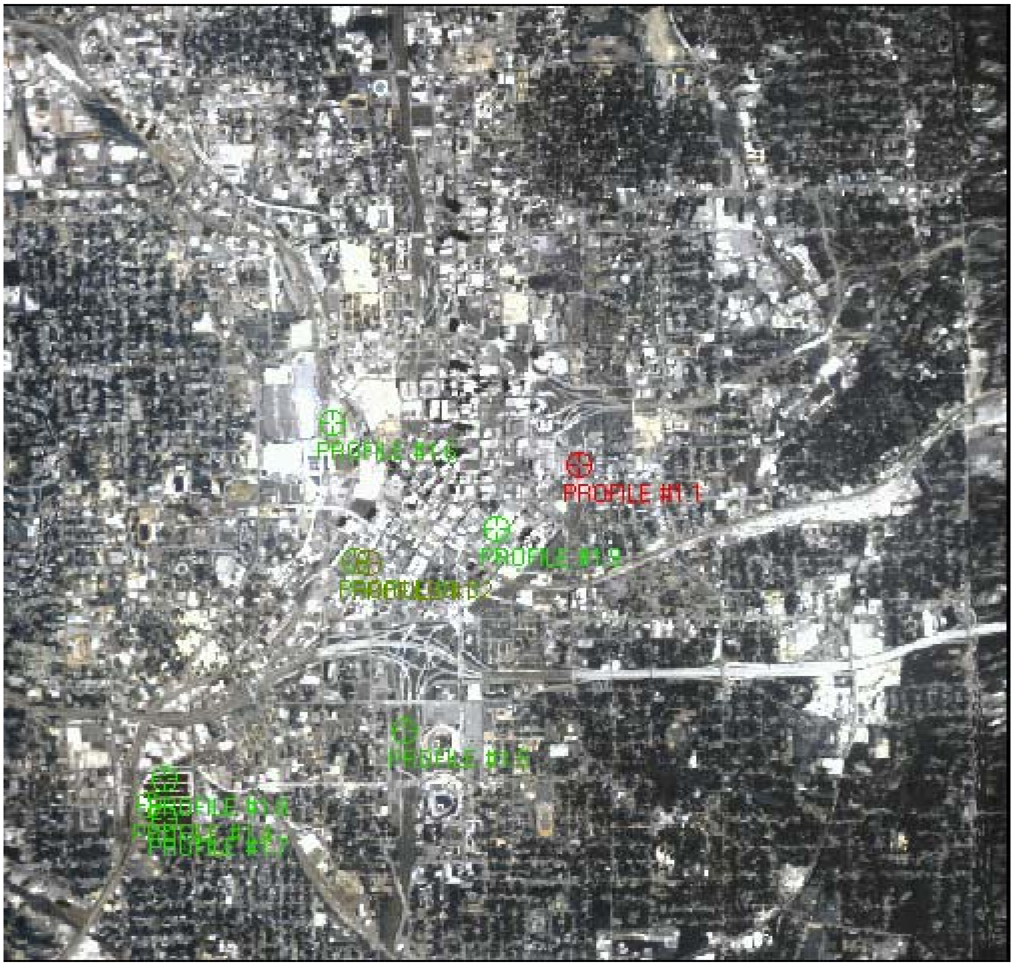

Figure 2. Visible image of downtown Atlanta with initial test locations.

The bands of particular interest in our investigation were the six new thermal infrared bands indicated in Table 1. The thermal bands range from 8.20 µm to 12.2 µm, and provide valuable information about urban landscape characteristics. A GPS location of the acquired data was used to ground-truth the information. The information for Atlanta was corrected for the attenuation effect of the atmosphere. The data were originally recoded as an 8 bit format with integer values ranging from 0 to 255. These values were adjusted for transmittance and path radiance variations, along with various calibrations for temperature measurements. This task was completed using the MODTRAN program developed by the United States Air Force Geophysics Laboratory. A section of the available data was cut out to provide a manageable amount of data to process and store.

Table 1. ATLAS channel specifications

	Channel	Band limits (μm)
Visible Bands	1	0.45 – 0.52
	2	0.52 – 0.60
	3	0.60 – 0.63
	4	0.63 – 0.69
Near Infrared (NIR) Bands	5	0.69 – 0.76
	6	0.76 – 0.90
	7	1.55 – 1.75
	8	2.08 – 2.35
Thermal Infrared (TIR) Bands	9	3.35 – 4.20
	10	8.20 – 8.60
	11	8.60 – 9.00
	12	9.00 – 9.40
	13	9.60 – 10.2
	14	10.2 – 11.2
	15	11.2 – 12.2

ROOFS, PAVEMENTS AND THE NORMALIZED DIFFERENCE THERMAL INDEX (NDTI)

This work is an expansion of research documented previously (McInerney et. al. 2006). In the previous work, the concept of an NDTI was proposed, and limited research using only the ATLAS thermal bands demonstrated the viability of the NDTI. Various image processing (IP) techniques were applied to the imagery, focusing in on the thermal bands (bands 10 to 15). Sixteen ground-truth points were identified as either rooftops or pavements. The points were used to determine the accuracy of the different analysis techniques. This paper documents our further exploration of the NDTI in relation to both the visible near-infrared and thermal bands, and proposes the most advantageous combination of bands.

Normalized Difference Thermal Index Analysis

A commonly used remote sensing technique is to divide the values of a sensor's different spectral bands at the same location by each other. A small ratio implies small change, and a large ratio means there is a greater spectral difference. This technique is used for many applications such as sensing minerals in earth ores. However, for more sensitive comparisons, a more sophisticated technique is shown in Equation 1.

$$\frac{\text{Band}(x) - \text{Band}(y)}{\text{Band}(x) + \text{Band}(y)} \quad (1)$$

This process is called a "normalized index" and results in values ranging from -1 to +1. The normalization allows for comparison between many different bands. The procedure is used to identify vegetation using the large difference in the absorption of the red and near infrared bands. Because we posit a thermal inertia between roofs and pavements, we suspected a reliable thermal index could be derived.

Procedure and Criteria for the Evaluation of the Normalized Difference Thermal Index (NDTI)

The Normalized Difference Thermal Index (NDTI) was calculated for each of the 180 unique combinations of the thermal bands. In analyzing the results the desire was to have the rooftops and pavements shown as distinctly separate. Statistical analysis of the NDTI technique was conducted to find the range, mean, and standard deviation of cells that were of the pavement or rooftop type.

To objectively evaluate how well each of the NDTI perform in distinguishing pavements versus roofs, we carried out the following procedure:

- For each NDTI we wish to evaluate, mask out all cells except those that are of the type in question (i.e. either pavement or roof, based on our ground control points).
- Apply an algorithm developed within our Geographical Information System (GIS) to consider only NDTIs that exist at our ground control points.
- From those of that particular type (either pavement or roof), find the range, the mean, and the standard deviation.

From this procedure we generated the statistics needed to evaluate the quality of the various NDTI. The criteria for a desirable NDTI are:

- For the same band ratio, the means should be as widely separated as possible
- For each cover type the peak should be well defined (i.e., the standard deviation should be small).
- For each cover type, there should be only one well defined peak.

Statistical Results of the Normalized Difference Thermal Index (NDTI) Analysis

An examination of the resulting statistics for all combinations show that bands 7 and 8 regularly appear in the top choices for correctly identifying roofs and pavements. For pavements, in order, the top 10 combination performers are presented in table 2. Bands 8 and 7 clearly dominate. Similarly the top roof combination performers are presented in table 2. Once again bands 8 and 7 dominate and although not in the same order, the same companion bands are present. It is interesting that to identify these materials well, the existing band 7 of the Landsat Thematic Mapper (TM) will do the job well. Thus, the question may be asked, “Is there any advantage in using the capabilities of the new ATLAS sensor over the sensors that currently exist?”

Although bands 8 and 7 are excellent at identifying pavements and roofs, this is unfortunately not the answer to our question. In addition to simply correctly identifying, these materials we must be able to separate roofs and pavements from each other. It would be helpful if the best identification of roofs and pavements, respectively, also provided the best distinction between them. As Figure 3 shows, such is not the case. So, it is necessary to trade off some ability to identify roofs and pavements correctly for an ability to distinguish between them. To do this, we must find combinations where the difference in the means between roofs and pavements is as great as possible.

When we rank the statistics by greatest difference in means, the NDTI combinations that are the best performers are very different. Table 3 presents the top five band combinations based on greatest separation of the means. From Table 3 it is clear that the new thermal infrared bands dominate.

Table 2. Best band combinations to determine Pavements (left) and Roofs (right).

Pavements				Roofs		
Bands	**Mean**	**Standard Deviation**		**Bands**	**Mean**	**Standard Deviation**
b3_b8	0.926165	0.009391		b6_b8	0.908232	0.016011
b1_b8	0.940455	0.009864		b1_b8	0.928867	0.018773
b2_b8	0.923891	0.010815		b3_b8	0.917677	0.018994
b4_b8	0.903840	0.012245		b2_b8	0.911280	0.021258
b5_b8	0.917798	0.014802		b5_b8	0.903334	0.020968
b6_b8	0.923959	0.017123		b4_b8	0.895039	0.024408
b5_b7	0.804007	0.014438		b6_b7	0.787398	0.030042
b1_b7	0.853382	0.027388		b3_b7	0.808295	0.039113
b6_b7	0.819479	0.024749		b1_b7	0.832974	0.041694
b2_b7	0.815379	0.024924		b2_b7	0.794330	0.043833
b3_b7	0.819949	0.028169		b5_b7	0.777117	0.041537

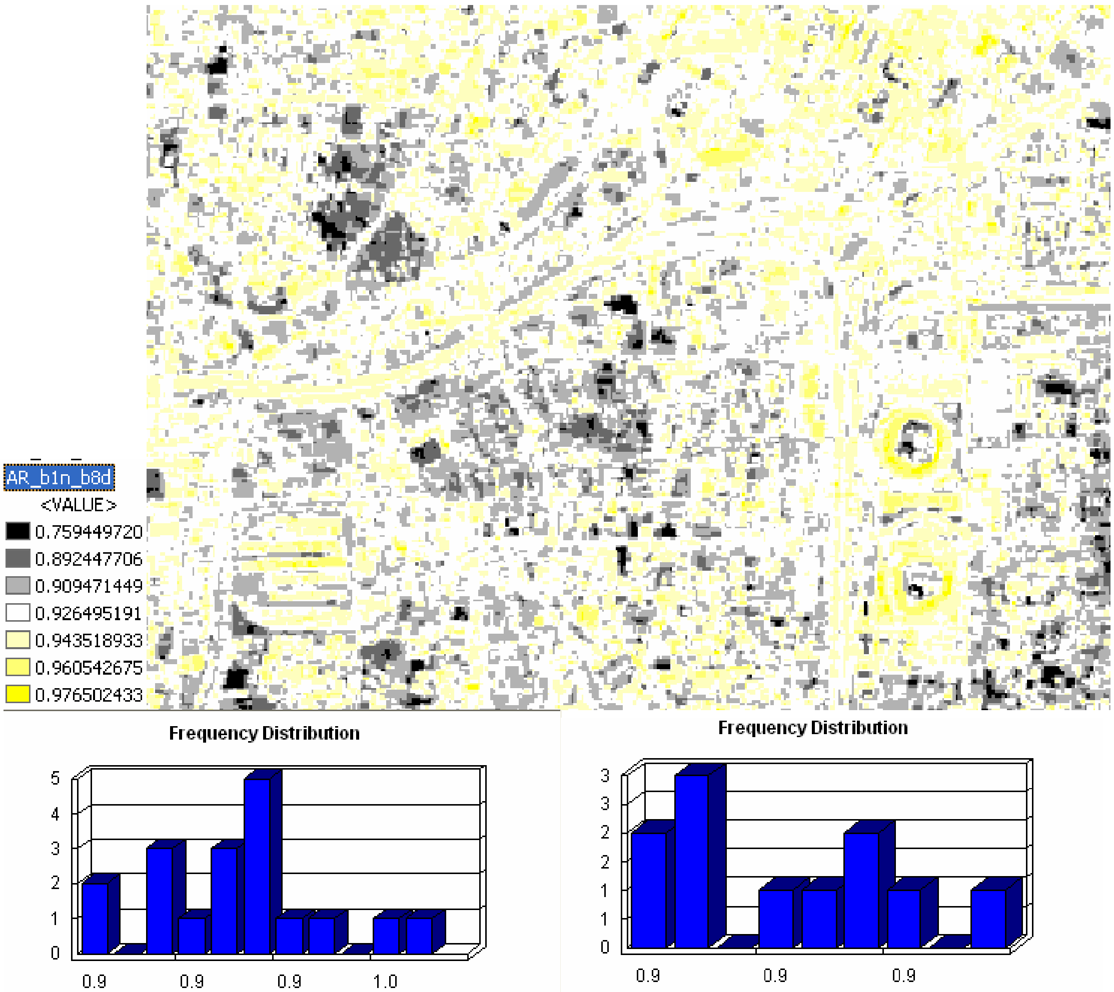

Figure 3. b1_b8 ranked high in being able to correctly identify roofs and pavements, but it is difficult to distinguish between the two cover types. The frequency distribution shows a tight clumping of NDTI values near 0.9 in a potential range of –1 to +1 for both pavements (left) and roofs (right).

Table 3. Best NDTI when ranked by best difference in mean.

NDTI Band Combinations	Difference in Mean	Roof Standard Deviation	Pavement Standard Deviation
b10_b15	.039	.096	.018
b10_b14	.038	.033	.016
b12_b14	.025	.012	.013
b13_b14	.023	.012	.005
b13_b15	.023	.012	.007

In our previous document (McInerney 2006), an NDTI generated from bands 10 and 15 was identified as likely to be useful for distinguishing roofs and pavements. When compared with all other combinations, this particular ratio still appears to hold promise (Figure 4).

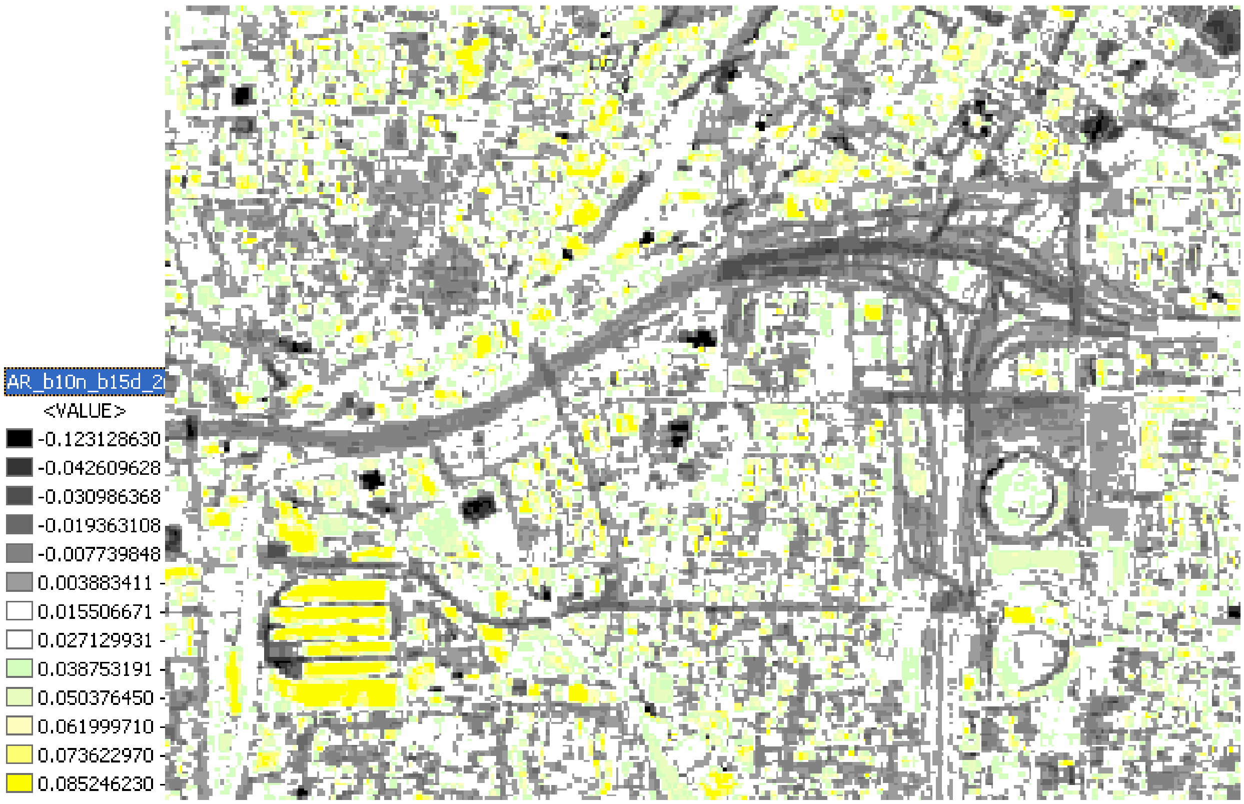

Figure 4. NDTI Image based on Bands 10 and 15. The categories are 1/2 Standard Deviation Intervals.

Another way of exploring the data is to rank the results by smallest average standard deviation (i.e., best defined peaks). Table 4 presents the top combinations using the best Standard Deviation criteria.

Table 4. NDTI when ranked by best average Standard Deviations.

NDTI Band Combinations	Difference in Mean	Roof Standard Deviation	Pavement Standard Deviation
b11_b12	.0004	.0027	.0048
b14_b15	.0003	.0087	.0043
b13_b14	.0233	.012	.0051
b13_b15	.0230	.012	.0070
b10_b11	.0104	.016	.0042

In order to obtain better peak definitions, have we traded off our requirement to separate the peaks? Certainly the difference in the means for the first two combinations, b11_b12 and b14_b15, is very small (i.e., separation is poor). Yet notice that for both b13_b14 and b13_b15 the mean separation is nearly 100 times greater than the first two combinations. Furthermore, both b13_b14 and b13_b15 showed up in Table 3 when we ranked NDTIs by best Difference in Mean. Since b13_b14 and b13_b15 appear in the top five either way, the implication is we are not making a large tradeoff when we adopt either a band b13_b14 or b13_b15 as the best-performing NDTI.

Do the b13_b14 and b13_b15 NDTIs seem to perform better than the previously identified top choice, b10_b15 NDTI?

Figure 5 shows the result using the same classification scheme as in Figure 4 (based on 12 classes of ½ SDs). A comparison of the results in the two study areas suggests that the b13_b14 NDTI (Figure 5) more clearly represents a distinction between pavements and roofs. In particular, smaller street pavements are visible and the confusion between roofs and pavements appears to decrease (likely due to the tighter Standard Deviations).

Figure 5. NDTI Image based on Bands 13 and 14. The categories are 1/2 Standard Deviation Intervals.

Observations Regarding This Analysis

Although the statistics and graphics show that the NDTI concept is viable, the physical explanation of why certain band combinations work well needs to be investigated. The physical science explanation for its sister index, the Normalized Vegetation Index, is well understood. The NDTI would be more readily accepted if research produced a corresponding first-principle physical rationale for its viability.

The NDTI is a simple initial step in the investigation of establishing urban structure through Thermal Remote sensing. A certain amount of confusion still remains in the resulting images. It is recommended that research on other image processing manipulation techniques (e.g., ratioing or principal components) be carried out to determine if an improvement of the NDTI algorithm's results can be derived. An understanding of the first-principle physical rationale for the NDTI would help direct this work.

One advantage of the NDTI is that the consequences of atmospheric absorption and solar incidence angle are minimized because the result is generated from a single image in which these considerations are largely held constant.

The conclusions of this investigation are based on only a few ground-truth points in a single location. It would be advantageous to expand the investigation to other locations with different ground-truth points to verify the universal viability of the concept.

FINDINGS

- The ATLAS thermal bands can be used to distinguish between roofs and pavements using the NDTI technique.
- The NDTI is a very useful concept because
    - It is easy to calculate,
    - To generate the NDTI only a single source image is required,

- It is inexpensive to produce.
- Groupings of bands tend to produce similar effects:
    - Bands 7 and 8 (combined with other bands) were shown to be effective at correctly identifying pavement and roofs. However, they were not adequate in terms of distinguishing between pavement and roofs.
    - The new, longer-wavelength spectral bands were more effective at distinguishing between pavement and roofs. Thus, imagers on currently available satellites cannot a substitute for these bands.
- NDTI based on bands 13 and 14 and bands 13 and 15 provide the best tradeoff between correctly identifying pavement and roofs and distinguishing between them.
- The previous research established the NDTI concept and provided a demonstration of its efficacy (but by using different NDTIs to distinguish between pavement and roofs). This research deals with the statistical comparison of all ATLAS band combinations and identifies two top contenders for establishing the NDTI.

CONCLUSIONS

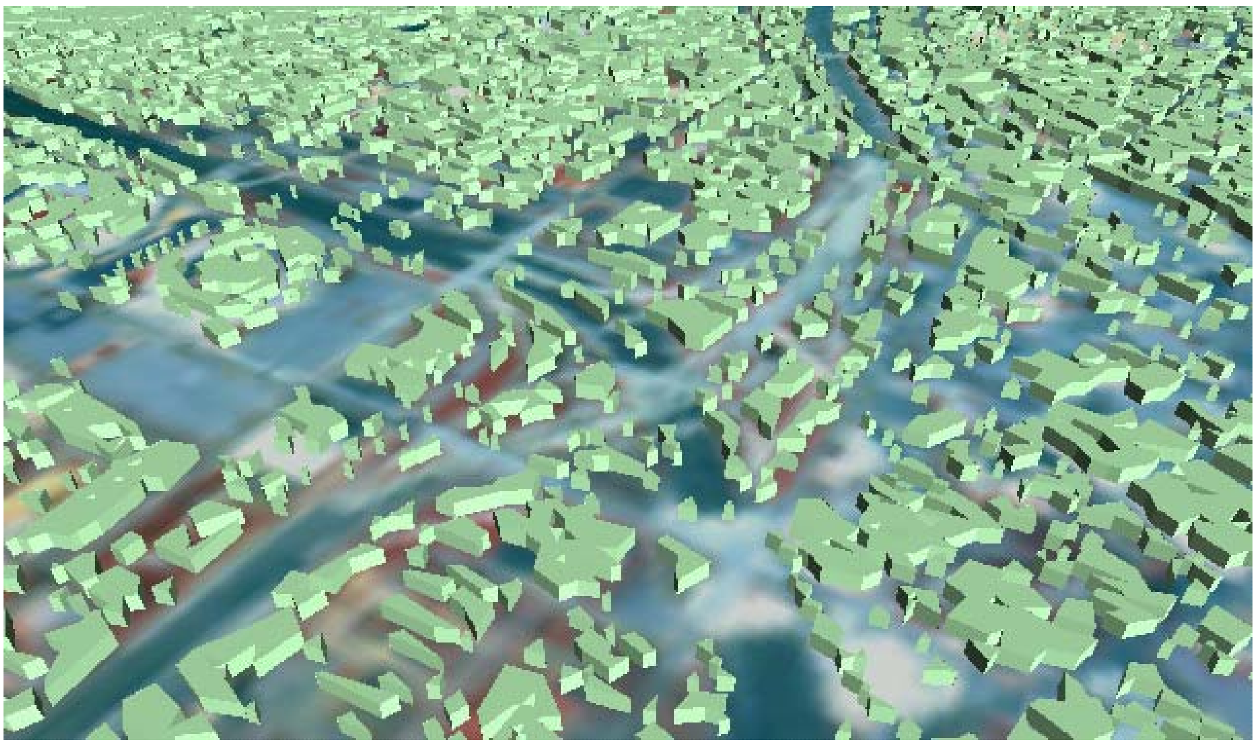

Figure 6. In this 3-D representation as determined from the NDTI of our Atlanta study area, the viewer is flying southwest above the Interstate 75 corridor. Circular Turner Stadium appears at upper left. From this viewpoint it is easier to see the curvilinear Interstate 20 (stretching diagonally from lower left to upper right). Although not perfect, this image shows well the general urban structure as derived from only two thermal bands. (Note that this 3-D image is intended merely to make the roofs stand out and is not representative of actual building height.)

The proposition we wished to test was, “Can we begin to develop a sense of urban structure by a simple algorithm based on the differential thermal inertia of pavement and roofs?” As

Figure **6** suggests, our initial sense is that it is possible to do so.

We tested the various band combinations of the ATLAS thermal spectral bands to determine how well we might be able to use these bands to distinguish roofs from pavements simply based on their thermal characteristics, that is, to develop a reliable Normalized Difference Thermal Index (NDTI). The best statistically determined choice was checked in detail against the stated criteria and was found to reliably fulfill the developed criteria. Previous research proposed two NDTIs be used, one to define pavements and one to define rooftops. This research finds that the NDTI based on bands 13 and 14 and bands 13 and 15 provide the best tradeoff between correctly identifying pavement and roofs and distinguishing between them. NDTIs from these bands produce well defined images that accurately identify ground-truth points. The purpose of this study was to determine whether Thermal/IR spectral data could be used to distinguish between pavements and rooftops in the urban environment.

It is suggested that different cooling rates due to the thickness and substrate may well be detectable if imagery taken at different times of the day were compared, particularly if mid afternoon imagery were compared to after midnight imagery. In this case, subtracting the daytime NDTI from the nighttime NDTI is likely to result in a clear distinction between the two materials. We plan to continue our study using data, both day and night, from the other cities in the NASA study.

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