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Thermal Infrared Imaging for the Charity Hospital Cemetery Archaeological Survey: Implications for Further Geological Applications

Raymond Heitger
University of New Orleans

THERMAL INFRARED IMAGING FOR THE CHARITY HOSPITAL CEMETERY ARCHAEOLOGICAL SURVEY: IMPLICATIONS FOR FURTHER GEOLOGICAL APPLICATIONS

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Raymond Albert Heitger

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Abstract

Recent work by Bob Melia of Real Time Thermal Imaging L.L.C. suggests thermal infrared (TIR) imaging can be used to identify subsurface archaeological features buried as deep as 3 meters but the basis for his work has not been tested. In November of 2002, Bob Melia and I attempted to locate unmarked graves at the Charity Hospital Cemetery using TIR imaging. Unfortunately, shortly after that survey, Bob Melia passed away without documenting his work or preparing the final report. Based on a review of previous research and modeling related to TIR imaging of subsurface features, I conclude that the high altitude that Bob Melia used for this type of study was key to his success. The larger field of view allowed recognition of longer spatial wavelength anomalies and more subtle temperature variations expected from features at greater depths than those in previous studies. Furthermore detecting features at these depths is aided by diurnal heating but is primarily made possible because annual seasonal temperature variations are significant 3-4 meters deep.

Introduction

Thermal infrared (TIR) imaging is a remote sensing method used to observe infrared energy radiated from an object above 0° K. The military developed TIR imaging with cameras for long distance surveillance during the 1940's. Since that time, technical improvements (Miseo and Wright, 2003; Wolfe and Zissis, 1993) and the relatively modest costs of the cameras have significantly broadened the scope of applications to include, for example, industrial material testing, searching for wiring shorts (e.g. Fournier et al., 2005), firefighting (e.g. Richards, 2004), weather studies (e.g. Moore, 2005), locating mold in walls (e.g. Brown and Brown, 2005), underground mine detection (Nguyen et al., 2005), SARS monitoring (e.g. Wallace, 2003), vegetation stress detection (e.g. Estep, 2004) and a continuously growing number of other uses (e.g. Richards, 2004; Harriman, 2004; Zhang, 2004; McKenna, 2000).

One of the pioneers in the development of new applications for TIR imaging, Bob Melia, produced archaeological discoveries (Woodall and Robinson, 2002; Yakubik and Melia, 2002; Melia and Yakubik, 2002; McCarthy, 2000) and possible new methods for mapping toxic waste spills in the near surface region (Melia, personal communication). Bob Melia's untimely death in December, 2002, shortly after he helped collect the TIR data from the Charity Hospital Cemetery (Figures 1 and 2) described in this study, left many unanswered questions about how he had achieved much of his success and how the technique could best be developed for future geoscience and archaeological applications. Thus, the primary purpose of this study is to continue his research by examining the scientific basis for his TIR imaging methods in order to create a basis for future applications.

To determine how Bob Melia used TIR imaging to identify archaeological features, I analyzed a copy of the original 8mm digital recording of the Charity Hospital Cemetery TIR data. It proved to be impossible to draw any definitive conclusions about how Bob Melia identified the grave sites, or to correlate the TIR data to the Ground Penetrating Radar (GPR) data (Shenkel et al., in prep) because of the lack of location information and quality of the copied video tape. However, I believe the TIR images do indicate recognizable subsurface features despite scientific studies (e.g. Li, 1995) that suggest TIR should not work for this type of study because of the depth of the objects of interest and the significant passage of time since the burials. Thus, I compared the assumptions and results of scientific studies on TIR imaging to the methods and ideas I had learned through conversation from Melia over several years to determine what might be the reason for his apparent success. I conclude that Melia's use of high altitudes for data collection and his ability to recognize and, perhaps bring out in processing, very subtle variations in the images has not been given sufficient consideration in the previous studies and those factors may be the key to his success in imaging archaeological features.

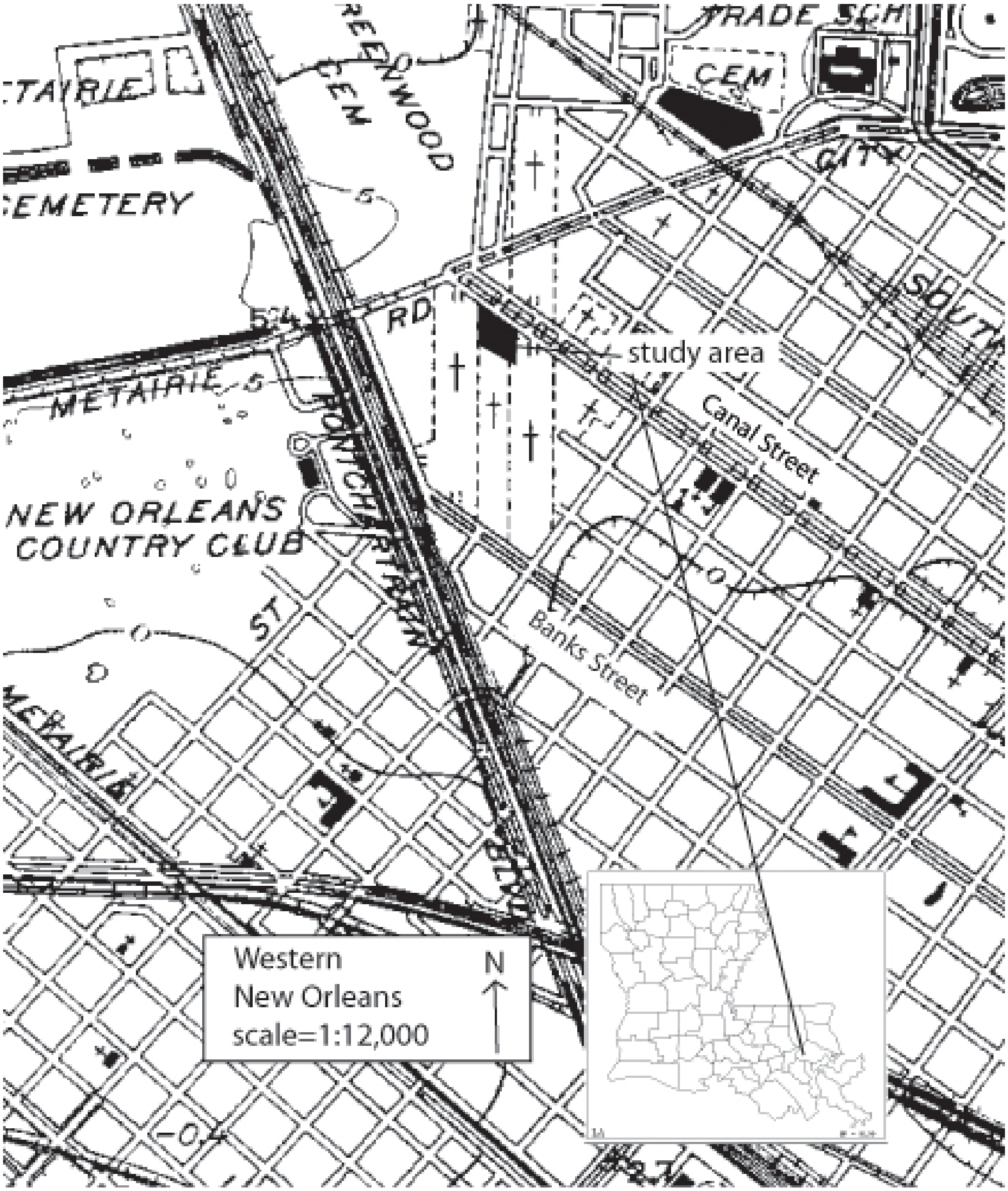

Figure 1. Location map for the Charity Hospital Cemetery in New Orleans, LA. The study area is the northern 200" of the Cemetery.

Thermal Infrared Imaging Methods

The TIR imaging technique is based on detecting thermal radiation contrasts between an object and its surroundings. All objects above absolute zero emit infrared radiation which can be detected with commercially available equipment such as infrared radiometers and cameras (Stohr et al., 1989). This radiation is a function of several physical characteristics of the object, including temperature, emissivity value—that is, the object's ability to absorb and radiate energy—composition, thermal conductivity, heat capacity, and density (Stohr et. al., 1989). For a more detailed explanation of the relationship between thermal dynamics and TIR imaging see appendices 1 and 2.

An infrared camera represents the emitted radiation in the field of view as points of varying intensity. The camera's lens focuses the energy onto a detector called a focal plane array which divides the field of view into thousands of small areas (pixels) (Miseo and Wright, 2003). The relative intensity of energy at each pixel determines how "bright" or "dark" the area is on the screen (Ruddock, 2003). An example of the TIR camera used in the Charity Hospital Cemetery and its specifications are shown in figure 3. Appendix 3 gives a more detailed description of the TIR camera and its basic operational principles.

TIR data can be digitally enhanced to improve the recognition of anomalies through a variety of standard image processing techniques (e.g. Norton and Dixon, 1996; Althouse and Chang, 1995). None of those techniques were used in this study but I believe that Melia would have used them to improve the recognition of the features he identified in the field because he had indicated to me (Bob Melia, personal comm., 2002) that he had made several improvements on the standard processing technology. I was unable to document those methods because of his untimely death.

A. PalmIR-250

Specification >	PalmIR 250
Detector Type	Uncooled Ferroelectric (320 x 240)
Spectral Response	7 to 14 microns
Startup Time	25 seconds @25°C
Thermal Stabilization	Thermoelectric Cooler
Video Update Rate	30 Hz - real time
Standard Lens	75 mm; f/1.0
Operating Temperature	-20°C to 49°C

Figure 3. The camera used in the Charity Hospital Cemetery Study and its specifications.

Landmine Detection Using TIR Imaging

Landmine detection is the most common commercial application that closely relates to subsurface geological and archaeological studies and it is the topic of numerous studies (e.g. Nguyen et al., 2005; Martinez et al., 2004; Baertlein and Sender, 2001; Li, 1995). Results of some relevant studies are given below.

Li (1995) conducted a comprehensive investigation of the capabilities of TIR imaging and buried object detection. Li systematically examined both theoretically and experimentally all the factors that characterize the surface thermal imprints and their relationships to (1) the buried objects and their geometric and thermal characteristics, (2) their distance from the surface, and the soil condition in which they are buried, and (3) the surrounding heating and cooling of the surface. Li found that the isotherm patterns above a buried object will reflect its shape. Furthermore, the deeper the object is buried the more diffuse the image. In fact, Li found that in the case of diurnal solar radiation heating, objects cannot be detected with depths exceeding 10 cm. Also, it was found that surface temperature change differences and the rate of temperature change due to diurnal changes produced by solar radiation can be measured and used to identify buried objects. But, it is a relatively slow effect with hours needed to observe temperature variations.

Baertlein and Sender (2001) employed numerical modeling to quantify the relationship between TIR signatures of buried land mines and various environmental conditions as well as the mine's composition, size, and depth. The environmental conditions included soil water content, soil sand content, and wind speed. The study found that soil parameters have little effect on the shape of the TIR image, but can significantly influence the amplitude and timing of optimum contrast. It was found that wind speed also can affect the signatures peak contrast but has no effect on the images shape. The depth of the mine (observed at 1.25 cm, 5 cm, 10 cm, and 20 cm) has a significant effect on the signatures amplitude and contrast but little influence on its shape.

Georgson and others (1999) also examined the effects of soil parameters on a TIR image. They looked at the signature of an aluminum clad wax object buried at depths of 5 and 15 cm and observed a measurable peak anomaly of 1-4° C during the hours of high radiation. They also noted that immediately after a burial of an object the thermal image will show the effects of digging rather than the object itself. In their tests, the digging dominated the image at the end of 2 weeks but the object was clearly apparent after 8 weeks.

Martinez and others (2004) presented a three-dimensional thermal mode of the thermal signature of landmines in bare soil. In this study, the landmines were modeled as thermal barriers (i.e. different thermal conductivity than the surrounding material) to the natural flow of the heat through the soil layers. The varying thermal conductivity of the landmine compared to the surrounding soil was shown to produce a recognizably strong anomaly (i.e. 1-5°C) in the thermal pattern on the surface from depths of up to 20 cm (Martinez et al., 2004).

Nguyen and others (2005) expanded on the work of Martinez et al. (2004) to consider varying soil conditions and weather. They also looked at the inverse problem of reconstructing the position, depth, and physical characteristics of a buried object from TIR data. Nguyen and others (2005) restricted their study to diurnal heating and depths of up to 48 cm. The 48 cm depth limit was considered sufficient for their study because they estimated an approximate 1-2°C temperature variation at that depth over a 24 hour period. The inverse modeling indicated they should be able to detect a landmine at a depth of 6 cm because it would produce a recognizable difference of +/-1°C in surface temperature variations over a period of 24 hours.

Archaeological Applications of TIR Imaging

The application of TIR imaging to archaeological studies appears still to be in its infancy. In fact, an article in the Handbook of Archaeological Sciences on geophysical methods (Nishimura, 2001) makes no mention of TIR imaging while earth resistance surveys, magnetometer surveys, GPR, and electromagnetic prospecting are all referenced as current methods used in subsurface mapping. Previous studies (e.g. Nguyen et al., 2005; Martinez et al., 2004; Baertlein and Sender, 2001), described above, showed that TIR imaging could be used to detect landmines at depths of up to 20 cm but greater depths were not considered in those studies. Li's (1995) more general results indicated that objects buried below 10 cm depth would not be imaged with TIR. Thus, because most archaeological applications require greater depths of imaging than 20 cm, TIR may be considered an unlikely tool for archaeological applications. Obviously, Melia was not daunted by the theoretical studies and he pursued the archaeological applications with apparent success (e.g. Woodall and Robinson, 2002; Yakubik and Melia, 2002; Melia and Yakubik, 2002; McCarthy, 2000).

Bob Melia

Melia did not publish a scientific analysis or justification of his methods but he kept copious notes (samples are included in Appendix 4). His services were often requested for the application of thermal imaging to archaeological studies and, in particular, grave detection. There are a number of newspaper accounts and reports (e.g. Woodall and Robinson, 2002; Naveaux, 2000; McCarthy, 2000; Knox, 2000; Associated Press, 2000; Post, 1998) citing the successful archaeological discoveries of Bob Melia with his thermal imaging techniques.

The U.S. Army Corps of Engineers recently worked with Bob Melia on two case studies (Melia and Yakubik, 2002; Yakubik and Melia, 2002) showing the impact thermal imaging had on buried feature detection. One study involved the discovery of an 18th century slave and labor community on the site of a former sugar plantation in Franklinton, Louisiana. A blind test was conducted to compare the results of different remote sensors to target objects for recovery. GPR, mag-spectrometers (ground conductivity), and TIR imaging were used at the site. The test site was 8 square acres and was "ground truthed" with positive archaeological data recovery (Melia, unpublished data). The thermal survey identified more subsurface details than any of the other techniques.

The other study was conducted in the general area of Port Hudson, north of Baton Rouge, La., where a confederate fort was suspected but not identified. A survey was conducted in the area to discover the road which was the center point of the fort. If the road could be identified then the exact location of the fort could be ascertained. The scope of the survey made GPR impractical and far too expensive. The infrared image produced a number of linear features which after cross-section excavation revealed a roadbed and some artifacts confirming the discovery of the original road.

In Salisbury, N.C., Melia conducted a study of a confederate prison. A monument on the site indicates that approximately 11,700 Union soldiers were buried in mass graves there. Historians have attributed that high number of deaths to malnutrition and exposure (McCarthy, 2000). In fact, TIR imaging revealed that the latrines were located much closer to the water supply than historians suspected leading to the likelihood of dysentery as the cause of death for most of the prisoners. Also, the actual number of deaths was closer to 4500 according to the TIR imaging.

His final work included a study of the Charity Hospital Cemetery in search for unmarked graves described below.

Charity Hospital Cemetery Project

The Charity Hospital Cemetery (Figures 1 and 2) is located in New Orleans, Louisiana. Its borders include Canal Street, Banks Street, Cypress Grove Cemetery, and St. Patrick's Cemetery Number 2. The cemetery had been used by Charity Hospital from at least 1843 to 1992 (George, 2002). It was originally known as Potter's Field (Salvaggio, 1992) and is the only completely subterranean cemetery in New Orleans. That is, all of the caskets are below ground and unmarked rather than in the above ground crypts that characterize all other New Orleans Cemeteries.

George, (2002) estimates the number of burials at more than 100,000 because the cemetery was a primary burial location during the epidemic periods in New Orleans. During the nineteenth century yellow fever, malaria, cholera, diphtheria, influenza, smallpox, and typhoid fever plagued the city and decimated the largely immigrant population (George, 2002). Another reason for the high estimate of burials in an area of roughly 60,000 sq. m is that during the 1930's the soil removed for the construction of a new hospital was added to the cemetery to raise the burial space by approximately a meter (Christovich et. al., 1974) and making room for another layer of graves. It was not uncommon for multiple bodies to be interred together and there is no evidence that any bodies have ever been removed from the cemetery.

In June, 2002, the Regional Transit Authority (RTA) of New Orleans commissioned R. Christopher Goodwin and Associates, Inc. to conduct archival research of the Charity Hospital Cemetery for the possible acquisition of the property. Mr. William Parrish of the Charity Hospital Trust Fund contacted Dr. Richard Shenkel of the University of New Orleans (UNO) Anthropology Department to perform a site characterization study of the cemetery to determine whether there was anything of historical or archaeological significance that would be prohibitive in the sale of the property. The report would include the location, orientation and condition of any unmarked graves. Due to the limited availability of burial records it was not known whether the interments were made in an orderly fashion or not. In order to keep the preliminary part of the project non-invasive, Dr. Shenkel contacted Dr. Laura Serpa, a UNO faculty member, for assistance in remote sensing.

The area of interest (Fig. 2) was the front 61 m (200 ft) of the cemetery at the main entrance on Canal St. because this was the potential site of a RTA depot. Dr. Shenkel oversaw the creation of a site map that included boundaries, elevations, and a grid for the GPR transects.

The Canal St. front is 89.4 m (293 ft) wide with sides measuring 61 m (200ft) and making angles of 55 and 135 degrees with the Canal St. side. A substantial section of this study area was excluded from assessment because of known prior or current ground disturbance. The excluded areas include a former flower shop (Figure 4a) located at 5060 Canal St, an adjacent parking lot, and the cemetery entrance driveway (Figure 4c) which was the location of a 1950's gas station. The gasoline storage tanks were removed at the beginning of this study. The remaining survey area consists of 28.6 m (94ft) behind the gas station along the St. Patrick's Cemetery border (Figure 4b), and 34.7 m (114ft) behind the building along the border of the Cypress Grove Cemetery (Figure 4d) (Shenkel, 2003).

The typical elevation of St. Patrick's Cemetery is roughly 0.26 m (0.85 ft) higher than the elevation of the Cypress Grove Cemetery (Shenkel, 2003). Thus, the elevation of Charity Hospital Cemetery's original surface would most likely lie somewhere on a gradient between the two border elevations. However, it is now noticeably higher than the surroundings. This is consistent with the reports of the deposit of large amounts of fill during the 1930's (Christovich et. al., 1974). The extra layer of soil is an important factor in the remote sensing data and calculating the number of burials because more recent burials were often placed on top of existing graves. Also, this type of burial practice could help in estimating the depth of the graves. It is possible that the Charity Hospital Cemetery contains unusually shallow graves which would be more easily detected with a TIR camera than the possible deep layer of graves that predate the fill.

Ground Penetrating Radar Survey

Between September 20 and September 24, 2002, Serpa and students (Figure 4b) (Shenkel et. al., in prep) collected GPR data in the cemetery. Data collection consisted of 87 profiles parallel to Canal St. and spaced 2 m apart. The Charity Hospital GPR survey revealed approximately 200+ anomalies (e.g. Figure 5) at depths of up to 2.0 m. However, few anomalies were observed at depths greater than 1.0 m where the caskets were expected to be (Serpa, personal communication). The absence of deep anomalies in the GPR data may have been due to the presence of clays in the soil, moisture from Tropical Storm Isadore which was approaching during the data collection, or a lack of burials in the region scanned. Because the GPR data did not appear to indicate many grave sites in the region, Bob Melia's offer to collect TIR data in the study area was readily accepted.

A. View of flower shop, single monument, and flags from the TIR survey

B. Lesley Quezergue collecting GPR data next to St. Patrick's #2 cemetery

C. Main roadway through the cemetery

D. Cypress Grove Cemetery next to the flower shop

Figure 4. Views of the Charity Hospital Cemetery survey area showing features mentioned in the text.

The Charity Hospital Cemetery TIR Survey

Bob Melia requested some altitude for optimum resolution and to enable the TIR camera to detect a range of temperature differences. Thus, a boom, or "cherry picker", was rented from a local heavy equipment company. The 40 foot arm of the boom provided the altitude for the survey. Most of the survey was conducted at a height of approximately 11 m (35 feet). The boom was placed at two different locations during the survey so the entire site could be scanned.

Bob Melia had extensive experience as a thermographer and was able to recognize thermal anomalies in the field as he recorded the data on tape. He interpreted those anomalies he saw as grave site locations and instructed the assisting students on the ground to mark with a flag or yellow spray paint the location of a suspected grave site. The boom basket on the cherry picker held 2 people so the students had an opportunity to view the images as Mr. Melia called for flag placements. This enabled the students to see what he was looking at when he interpreted the presence of a grave site.

Hundreds of locations were marked. Many were marked at roughly 1 meter intervals and seemed to form rows indicating the likelihood of burials. Some locations were interpreted as a multiple grave site and were marked with a yellow spray paint circle around a flag. The high number of suspected grave sites seems to be consistent with historical estimates (George, 2002).

The camera Melia used (Figure 3) has the ability to display different levels of emitted radiation as tonal contrast on a real-time image. This camera is able to display the images in "black hot" or "white hot". As the name suggest, in the "black hot" setting, the darker areas on the image indicate higher levels of radiation. Most of the survey was conducted with the camera set on "black hot" (e.g. Figure 6).

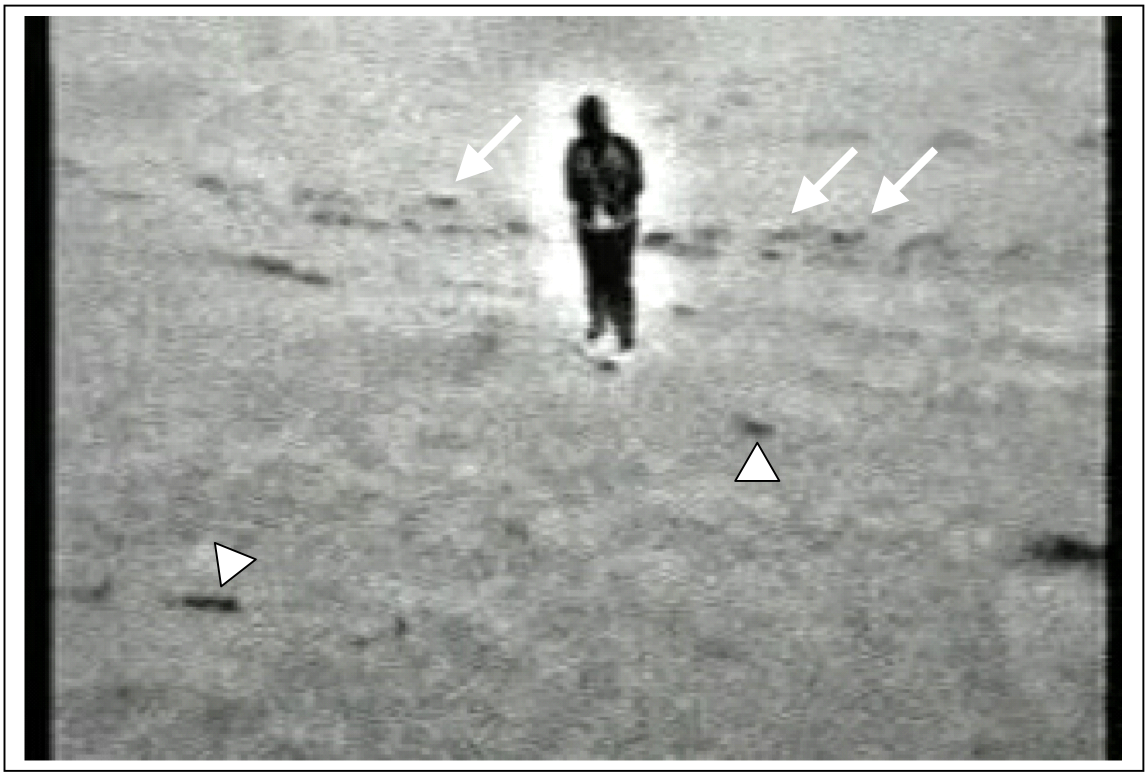

Fig. 6: TIR image of Charity Hospital Cemetery in the “black-hot setting”. Arrows indicate warmer features such as grass cuttings, arrowheads point to possible grave markers.

Data Analysis

The entire TIR survey took approximately 2 ½ hours to complete. At this point the intention was to use some of Bob Melia's proprietary software to enhance and analyze the data to produce a TIR map of the site. However, the post survey analysis of the infrared data did not occur because of the untimely death of Melia. It was clear during the survey that Melia was confident he was identifying grave sites from the thermal signatures that he was observing on the camera screen. Subsequent minimal excavations (i.e. "ground truthing") in 3 locations (Shenkel, et al., in prep) confirmed that there were in fact graves nearly a meter deep in the locations indicated by Melia on the basis of the thermal imaging experiment (Figures 7, 8, 9a, b).

I had difficulty, however, reconstructing the thermal anomalies that Bob Melia had pointed out. It appears that some information or detail may have been lost when the digital 8mm recording was converted to the VHS video I had to work with in post survey analysis. Also, the locations of the video sequences were lost with Melia's death. He may have had a standard pattern in which he shot this type of data but that pattern could not be discerned from the copy of the video tape that I had. I was unable to compare the TIR data with the GPR data or to construct a map of the observations because there was no location information available for the TIR data except in a few places where we could recognize some landmarks in the area. The monument near the flower shop (Figures 2 and 4) was near one of the excavations and it provided some location information for that area of the TIR data.

Figure 7: Excavated location flagged by TIR imaging. Grave identified at nearly 1 meter deep.

Figure 8: Second excavated site confirming grave location at approximately 1 meter.

Figures 9a (above) and 9b (left): At depths ranging from 13cm to 19cm rows of cement marker blocks were uncovered.

The survey team (i.e. Richard Shenkel, Laura Serpa, Juana Ibanez, Lesley Quezerque, Monique Mitchell, and I) met to try to identify thermal patterns on the video that might be consistent with a grave location. It was interesting because each person had some preconceived idea of how the image might appear from their contact with Bob Melia during the data collection. Some members were looking for very pronounced contrast in tonal definition. Some thought there may be only subtle variations. Others were searching for straight lines which indicate something man made because Melia had indicated that was an important criteria. There was also significant discussion and speculation concerning the size of a thermal signature created by a burial. The TIR images did indicate some small pronounced anomalies that the team suspected could have been name tags (Figure 6) used to mark burials at that time.

Unfortunately, there were no definitive interpretations made in our post survey analysis. The team did conclude that there were variations in the thermal images that could certainly indicate grave sites (e.g. Figures 10-13). For the inexperienced thermographers however, it was difficult to distinguish between vegetation, grass cuttings, other "noise", and a true thermal signature of a grave.

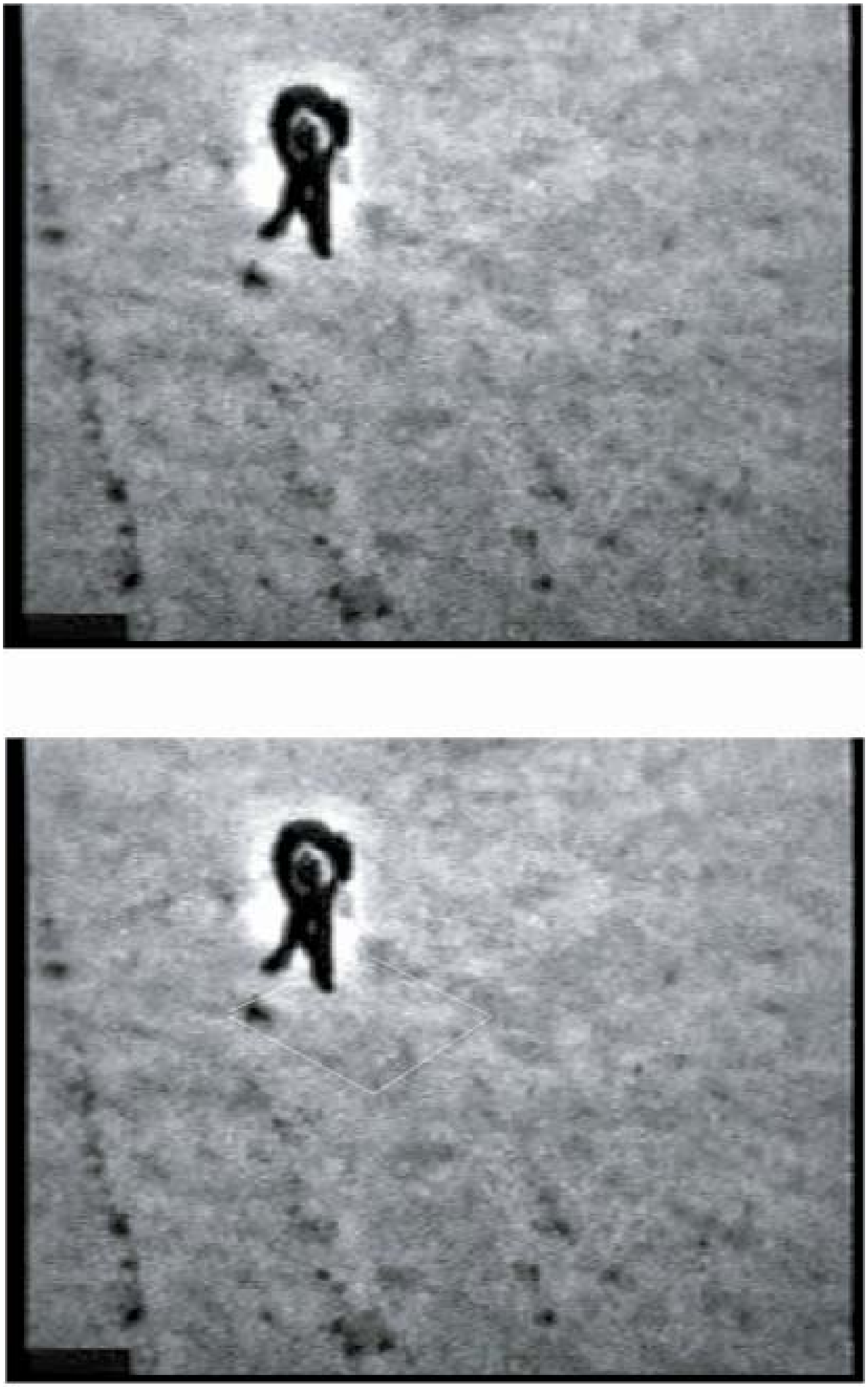

Figure 11. Thermal anomaly (outlined in lower image) in the process of being marked.

Fig. 13: TIR image showing a suspected location of a grave. The unmarked photo is given in the upper panel and the lower panel shows an outline of a possible grave.

Discussion

I was not able to reproduce the observations of Bob Melia for the Charity Hospital Cemetery when I reviewed the tape of the TIR data for the first time. The major reason for this is probably my inexperience with this type of data. However, after further scrutiny of the images, I was confident that subsurface features were evident on these images. Because I had known Melia for many years and he had spoken with me often about his work, I felt I might be able to examine the methods he used and what he felt were important parameters for archaeological work to get an idea of what was the cause of his successful use of TIR imaging. Then, I compared his methods to tested techniques and tried to identify what was unique with Melia's approach to detecting subsurface features.

Unmarked grave detection methodology derived from personal conversations with Bob Melia

Bob Melia indicated to me a number of techniques that he felt were particularly important in designing and collecting useful TIR data. These included: collecting data in dry weather, collecting data in the late afternoon or early evening with additional check scans of the area during both solar cycles, looking for straight lines, and using altitude to increase the field of view. Thermal modeling (e.g. Baertlein and Sender, 2001; Georgson et al., 1999) does indicate that moisture content, wind speed, soil type, and ground roughness do affect the quality of the TIR imaging.

According to Melia, as the ground goes through the solar cycle, the ground with grave features will heat and cool at a slower rate than the surrounding soil. As the earth enters its cool down cycle, subsurface features associated with burials such as brick footings or structural foundations retain the heat longer and are easily discernable as linear or geometric features. Melia identified this as the signature of a man-made structure. This is consistent with Li's (1995) findings that objects with different thermal characteristics have different rates of heating and cooling. Furthermore, the objects thermal signature will resemble its actual size and shape.

Melia indicated that the optimum time to conduct a thermal survey would be late afternoon or early evening and that a scan of the area during both solar cycles actually increases accuracy and confidence in the interpretation. This result is very similar to that observed by Martinez and others (2004) and Nyugen and others (2005) that the peak of the solar cycle or soon thereafter produced the maximum anomaly. Both studies showed there were times when no discernable anomaly could be expected to be measured and that would support Melia's suggestion that scans should be conducted at other times of day to confirm the quality of the anomalies.

One aspect of archaeological studies that is particularly difficult to deal with is the apparent lack of penetration of a heat source to the depths of 1-2 meters that might be necessary for TIR imaging of graves or buried artifacts. A simple thermal calculation (e.g. Fowler, 1990, pg. 231) indicates that diurnal variations should not be significant below a depth of 15 to 20 cm and that is consistent with the findings of Li (1995). Nyugen and others (2005) found that they had no significant temperature variation due to diurnal heating below a depth of 48 cm. That depth, 48 cm, is within the realm of some archaeological interest but should not be particularly useful for grave detection.

Melia felt that when a grave is dug and filled, weathering would cause the soil in the grave socket to compress. This results in a varying soil density between the grave and the surrounding soil. This density difference creates different thermal characteristics that Melia believed were easily detectable with an infrared image. Thus, he would suggest that even if the temperature variations did not penetrate to the depth of the object itself, the differential compaction or weathering of the overlying soil might be detectable with TIR imaging. This particular assumption contradicts the findings of Georgson and others (1999) who found that the evidence of digging was not detectable after 8 weeks.

Melia was particularly insistent on the use of altitude to collect archaeological data. He indicated that the best results are obtained from an aircraft, preferably a helicopter, at an altitude of 200-300 m and a speed of 60-80 knots. The altitude increases the probability of detecting small thermal variations. A man-lift can also be used for a small area, as was the case with the Charity Hospital Cemetery survey, but the field of view for thermal comparison decreases. Scanning from ground level becomes extremely difficult because the field of view is small.

In addition to the objections indicated above, there are other obstacles to using TIR data for archaeological purposes (Melia, personal comm.). These include masking of the anomalies by vegetation, cultivated land, plow zones, underground utilities and standing water. An experienced operator, like Melia, apparently can recognize the scurrilous signals and often separate them from the desired anomalies without additional processing. However, image processing of the data also could be used to bring out subtle features or patterns that may not be apparent to an untrained eye. Melia did use processing to enhance his images but he apparently was quite skilled at recognizing the anomalies in the raw data. Most of the examples of the archaeological surveys that Melia presented were qualitative in nature and simply required the recognition of subtle variations in an image.

Conclusions and Recommendations

Melia believed he could record thermal anomalies produced by diurnal heating at depths of a few meters. At those depths, there would have to be sufficient temperature variation between an object and the surrounding soil to be represented on the surface and detected with a TIR imaging camera. None of the previous studies indicate it would be possible to image an object at depths in excess of a few 10's of centimeters with a TIR camera so initially it would seem unlikely that Melia would have had success with his approach. However, none of the studies indicated above considered temperature variations of a few tenths of a degree but the camera Melia used (Figure 3) was capable of detecting surface temperature variations of 0.1°C. Melia did work with very subtle variations that might have indicated very small temperature changes.

In addition, although diurnal temperature variations might not penetrate to the depths of archaeological interest, seasonal variations (e.g. Fowler, 1990) are significant at depths of 3-4 meters and the widespread use of heat pumps to heat and cool homes in the southern U.S. indicates this is a significant thermal variation. Thus, the heat source for deeper features might be seasonal rather than diurnal in many cases or some combination of the two sources to support Melia's suggestion that TIR data should be collected late in the day.

Finally, Melia's use of altitude to get a wide field of view would also allow him to compare temperature variations over a wide area where a pattern of small variations might become more recognizable. In many geophysical applications, increasing depth of burial would produce an increasingly longer spatial wavelength anomaly which might require the greater field of view to recognize. Similarly, if the thermal source is seasonal temperature variations rather than diurnal variations then the thermal response might also be spread out over a large area.

In Summary, Melia appeared to be able to image archaeological features and grave sites using TIR imaging. His success may have been due to his ability to recognize subtle variations in his data, radiation due to seasonal temperature variations, his use of altitude to image a wider range of surface temperature variations and longer spatial wavelength anomalies or some combination of those factors. None of the previous scientific test (e.g. Nguyen et al., 2005; Martinez et al., 2004; Baertlein and Sender, 2001; Li, 1995) that I could identify have addressed these factors in sufficient depth to determine whether they are a factor in archaeological surveying with a TIR camera. Thus the next step in developing TIR imaging should be more appropriate testing of the method.

In particular, I recommend that similar comprehensive studies, as were done to determine the capabilities of TIR imaging for landmine detection, be adapted to TIR imaging for archaeological and geological applications. The same variables that influence TIR images of landmines such as the effects of (1) the buried object on the surface; (2) the object and its thermal characteristics; (3) the size and shape of the feature (4); soil medium and condition; (5) rate of heating and cooling of the surface and other environmental conditions such as air temperature and wind speed, and (6) optimum observation time, must be examined and their relationship to TIR images with archaeological and geological depths established.

I recommend extensive experiments, with the above mentioned variables controlled, to determine how deep a TIR device can image and the altitude necessary to achieve maximum depth. Previous studies mostly observed relatively large temperature variations of 1-2°C while concentrating on imaging objects at depths of a few tens of centimeters. I believe that we can detect objects at greater depths by observing more subtle temperature variations but this theory needs to be vigorously tested. Also, the effects of annual seasonal temperature variations and their influence on subsurface features a few meters deep should be examined. I believe that simply burying an object a few meters and immediately observing its TIR signature does not take into account this effect and is an inherently flawed experiment. The buried features will need to be observed over time, possibly a year or two.

Finally, Georgson and others (1999) found that the effects of digging dissipate after time. Hence, I recommend attempting to establish how long it takes for the effects of digging a few meters deep, rather than tens of centimeters, to diminish.

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Appendix 1

Infrared Imaging

Infrared imaging, or infrared thermography, has broad applications and is emerging as one of the most useful forms of remote sensing today. Energy radiated from an object is collected, converted into an electrical impulse, and displayed directly to a video monitor for real time evaluation. A gray scale or a color display is used to indicate different energy levels (Baraniak,1983).

All objects above absolute zero emit infrared radiation which can be detected with commercially available equipment such as infrared radiometers and cameras (Stohr et al., 1989). These systems generally register radiation in the 2-6 micrometer or short wavelength band and the 8-14 micrometer or long wavelength band (Baraniak, 1983).

It is a common misconception that infrared systems measure temperature. They detect the radiated energy given off from the first 1/1000 of an inch of the surface of an object (Ruddock, 2003). This radiation is a function of several physical characteristics of the object only one of which is temperature. Other characteristics include the material's emissivity value, that is, the object's ability to absorb and radiate energy - its composition, thermal conductivity, heat capacity and density (Stohr et al., 1989).

Both qualitative and quantitative analysis can be performed with thermal imaging. It is possible for an experienced thermographer to calculate the precise temperature of an object from its infrared signature (Baraniak, 1983). Today, with sophisticated imaging radiometers, infrared thermographers are able to register thermal patterns with temperature variations as little as 0.01 degrees Celsius.

For the Charity Hospital Survey, we used a qualitative approach to locate grave sites by identifying thermal anomalies - that is, variations in the amount of infrared energy radiated from the ground. In some cases, however, an actual temperature calculation of an object is required. In this case, several parameters must be identified in order to measure an accurate temperature. These include the emissivity of the material and the relationship of an object to its environment with regard to solar loading, wind speed (if applicable), and moisture (Baraniak, 1983).

Temperature is a scalar quality that defines the molecular energy of a substance (Sears and Zemansky, 1973). Heat, on the other hand, is the energy transferred between two objects of different temperature (Browne, 1999). Therefore, temperature defines an object's ability to impart energy to another object. When two objects in contact with one another have the same temperature, energy transfer does not occur and the objects are said to be in thermal equilibrium.

This simple concept is extremely important in a qualitative TIR survey because the thermographer is looking for a thermal anomaly which would indicate an object that exhibits a different thermal characteristic from its surroundings. One thermal characteristic may be the object's *heat capacity.* When heat is added to a substance, the substance will become hotter, and thus, radiates more infrared energy. The resulting rise in temperature, ΔT, is dependent on several factors including the object's mass, its composition, and the heat added to the system (Browne, 1999). The amount of heat required to raise the temperature of a substance by 1°C is its heat capacity. *Specific heat,* c, is a function of the heat required to raise 1 Kg of a substance by 1°C. So if heat, Q, causes mass, m, to change temperature by an amount ΔT, then $c= Q/(m\ \Delta T)$

Specific heat is a thermal characteristic that is unique to a given material. As a result, different materials heat up at different rates. Rate is implied in the equation when there is a change in temperature with respect to the same unit of time. For example, throughout the day, diurnal heating warms the soil as well as a buried object of interest. The object, because of its composition, has a different specific heat than the surrounding soil. Since the energy source is uniform it will take one material longer to raise its temperature because of the extra heat required to do so. As the material that is more easily heated rises in temperature it also radiates more infrared radiation. This will create contrasting thermal patterns on a thermogram. This concept is helpful in exploiting optimum survey times when temperature differences are at their greatest resulting in more pronounced thermal anomalies. For instance, in the case of identifying subsurface features, conducting the TIR study at the end of the solar warming cycle will most likely produce the best results.

When objects are not in thermal equilibrium, heat transfer can be achieved by conduction, convection, radiation, or some combination of the three mechanisms (Browne, 1999). Each of these mechanisms produces a specific thermal pattern which will aid a thermal technician in data analysis.

Conduction is heat transfer by the intimate contact or collision of molecules. This can occur in any state; solid, liquid or gas, as long as there is a temperature difference. Conduction is the only mechanism by which heat flow occurs in a solid. A distinct thermal pattern is created by heating due to conduction. Generally, the thermal signature of conduction shows progressively varying tones on the image. Consider an object with a cross-sectional area A and a thickness Δx. One side of the object is maintained at temperature T_1 and the other at T_2. Experimentally it is shown that the thermal energy ΔQ that flows through the object in time Δt is $\Delta Q = kA (\Delta T/\Delta x)\Delta t$, where $\Delta T = T_2 - T_1$ and k is the *thermal conductivity* of the object (Browne, 1999).

The thermal conductivity of an object is another thermal characteristic of a material that contributes to the material's ability to radiate energy.

Convection is heat transfer by the movement of material. As thermal energy excites the molecules in a fluid or gas, the molecules move further apart and the material becomes lighter thus floating upward carrying thermal energy with it (Browne, 1999). The cooler, denser areas of the material begin to descend due to gravity. Again, convection provides a distinct thermal pattern. Its pattern is usually "wispy, and uneven" (Ruddock, 2003). Recognizing these patterns due to convection could be very helpful in assessing contamination spills involving fluids.

The third mechanism is heat transfer by radiation which involves the transfer of energy from one solid or liquid to another by alternating electromagnetic waves traveling through a gas or vacuum (Sears and Zemansky, 1973). There are many different forms of electromagnetic radiation that are described by their varying wavelengths. Heat transfer by radiation occurs primarily in the infrared band of the electromagnetic spectrum. As thermal energy, or heat, is added to the surface of an object, the kinetic vibrational energy of the molecules increase and more infrared radiation is emitted. When this radiation strikes another object the energy is absorbed. If the second object was cooler, the added energy would cause the molecules of the cooler object to vibrate faster therefore increasing its temperature. Some distinction has to be made between radiated energy and heat transfer by radiation. By the definition of heat transfer a variation in temperature between objects must be present. Unlike the previous two mechanisms of heat transfer, radiation can take place even when there is no material between the radiating and receiving objects.

Radiated energy does not require a temperature difference. All objects above absolute zero give off infrared energy due to the emission of electromagnetic radiation (Sears and

Zemansky, 1973). The power radiated from a surface area A at temperature T is given by the Stefan-Boltzmann law**,** which states that the amount of energy radiated by an object is proportional to the objects temperature in Kelvin raised to the 4^{th} power.

This means that a small change in temperature will result in a large increase in radiated energy (Ruddock, 2003). This explains why infrared cameras are very sensitive to small temperature variations.

Emissivity is one of the most important thermal characteristics a material possesses for it recognizes the object's ability, or inability, to radiate energy. Emissivity by definition is the ratio of energy emitted by an object compared to that of a blackbody at a given temperature and wavelength (Sears and Zemansky, 1973). A blackbody is defined as a perfect radiator. In 1858 Gustav Kirchhoff discovered that an objects ability to emit infrared radiation was equal to its ability to absorb it (Ruddock, 2003). Since a blackbody absorbs 100% of the energy that strikes it, a blackbody is then a perfect emitter. So, a blackbody radiates the maximum amount of energy at all temperatures and wavelengths.

The emissivity of an object is characterized by the material of the object, the surface condition of the first 1/1000 inch, its temperature, the wavelength the object is viewed in, and the geometry of the area viewed. Knowledge of an object's emissivity value is integral in analyzing an infrared image and making assumptions about an objects thermal qualities. Table 1 shows some emissivity values for a variety of materials (Baraniak, 1983).

Table 1: Selected Emissivities (adapted from Baraniak 1983)

Material	(°C)	*Temperature*	*Emissivity*
METALS AND THEIR OXIDES			
Aluminum:	polished sheet	100	0.05
	sheet as received	100	0.09
	anodized sheet, chromic acid process	100	0.55
	vacuum deposited	20	0.04
Brass:	highly polished	100	0.03
	rubbed with 80-grit emery	20	0.2
	oxidized	100	0.61
Iron:	cast, polished	100	0.02
	cast, oxidized	40	0.21
	sheet, heavily rusted	100	0.64
Stainless steel:	type 18-8, buffed	20	0.16
	type 18-8, oxidized at 800 °C	60	0.85
OTHER MATERIALS			
Brick:	red common	20	0.93
Lacquer:	white	100	0.92
	matte black	100	0.97
Oil, lubricating	nickel base alone	20	0.05
(thin film on	film thickness of 0.001, 0.002,0.005 in.	20	0.27, 0.46, 0.72
nickel base):	thick coating	20	
Paint, oil:	average of 16 colors	100	0.94
Soil:	dry	20	0.92
	saturated with water	20	0.95
Water:	distilled	20	0.96
	ice, smooth	-10	0.96
	frost crystals	-10	0.98
	snow	-10	0.85

Appendix 2

Electromagnetic Radiation

Electromagnetic radiation is the transfer of energy due to alternating electric and magnetic fields. This radiation travels at the speed of light, 300,000 kilometers/second, in the form of an electromagnetic wave that exhibits electrical and magnetic properties. Electromagnetic radiation is the result of charged atomic particles accelerating and decelerating from their point of origin (Browne, 1999).

Essentially all electromagnetic radiation is the same. What differs between radio waves, microwaves, gamma waves, ultraviolet radiation, infrared etc. are the wavelength/ frequency of the waves. The following electromagnetic spectrum is an energy chart that illustrates these differences (Figure 14). The shorter the wavelength along the electromagnetic spectrum the more energy is required to produce the radiation.

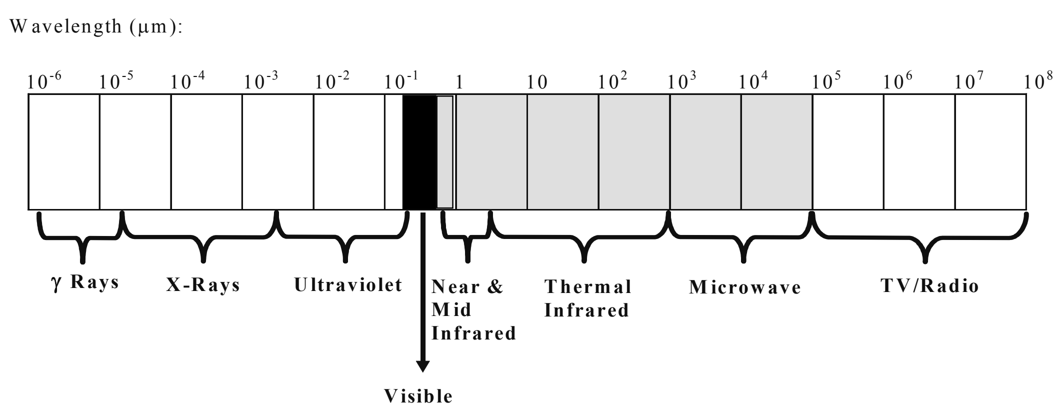

Fig.14: The electromagnetic spectrum (modified from Sears and Zemansky, 1973)

Another distinguishing feature of one form of electromagnetic radiation from another is how it is created and received. For instance, the Ground Penetrating Radar used in this survey produced radio waves at roughly 15,000 MHz with a wavelength between 10-1 cm. The radio waves are produced by agitated electrons. Radio waves are transmitted by an omni directional aerial and received by a radio receiver (Ruddock, 2003).

The Infrared region, on the other hand, is the portion of the electromagnetic spectrum between red visible light and microwaves (1-1000 microns). This region can be divided into 3 spectral categories. These categories include the near infrared region, between 0.72μm and 1.3μm; the middle infrared region, between 1.3μm and 3μm; and the far infrared region, between 7μ and 15μm. Higher energy levels correspond to smaller wavelengths. Infrared radiation, in general, is invisible to the human eye. It is not until radiated energy levels leave the near infrared region and approach the visible light spectrum that this radiation is detectable with the eye. A simple experiment utilizing an electric stove shows that when the temperature of the burner is only warm, the human eye cannot see that the burner is, in fact, radiating heat. As the temperature increases, however, the eye sees the burner begin to glow red/orange (Baraniak, 1983). Infrared film associated with infrared photography has similar constraints. Conventional infrared film which is sensitive to about 0.9μm cannot image thermal emitted infrared energy (Baraniak, 1983). The temperature of an object must exceed 400°C (752°F) before infrared film will document this radiated energy. Specialized detectors which operate in selected wavelengths combined with optics which are transparent to infrared energy, therefore, must be used to detect and amplify thermally emitted infrared radiation (Baraniak, 1983).

Appendix 3

The Infrared Camera and Its Basic Principles

The instrument used to receive infrared radiation is often an infrared imaging camera. Generally, infrared systems come in several different wavelength classes. Some cameras, which utilize infrared photographic film, work in the visible to near infrared region at roughly 0.9- 1.7 μm. These systems are used to detect reflected radiation from the sun or other light sources (Baraniak, 1983). The observation of reflected energy is particularly useful when thermal imaging is applied to vegetation studies. Healthy vegetation reflects light differently than unhealthy vegetation due to drought, infestation, or disease. Healthy vegetation usually contains higher amounts of water which produces a lighter almost pink color in contrast to the brown color dead or dying vegetation produces (Ruddock, 2003).

Other cameras, known as short wave systems, are sensitive to the 2-6 μm range, and long wavelength cameras work in the range of 8-14 μm. The short and long wave systems are most commonly seen in industrial applications (Ruddock, 2003). For the Charity Hospital Cemetery project the Raytheon Palm IR 250, a long wavelength system, was used (see figure 3 for description and illustration).

It is important to remember that the infrared camera does not directly view the scene, rather it converts radiated energy into an electronically produced image that represents the field of view. Because infrared radiation cannot be seen with the naked eye, specially developed detector systems known as Focal Plane Array systems divide the field of view into thousands of specific areas. Radiated energy is collected independently from each specific area and converted into an electrical impulse. This electrical impulse is then displayed as an image on the cameras screen. The electrical value for each sensing element, or pixel, determines how "bright" or "dark" the area is on the screen (Ruddock, 2003). Generally, the areas of the image that appear brighter correspond with higher levels of radiated energy. In the past, infrared devices produced black and white images that emphasized tonal differences. Present day cameras have the ability to assign a false color scheme to the electrical data which then produces a color infrared image.

Infrared imaging systems can be classified as cooled or uncooled systems. In the past most systems were cooled with liquid nitrogen, or a stirling cycle cooler, and contained photon detectors. Cooled detectors collect radiation and observe the interaction with the materials electrons. The observed signal results from the change in electrical distribution. Today, most of the systems use the new Focal Plane Array technology and are often uncooled (Ruddock, 2003). Uncooled thermal detectors operate on a very simple principle. Incoming infrared radiation will heat the systems detectors and measure the temperature changes with temperature-dependent mechanisms such as thermoelectric voltage, resistance, or pyroelectric voltage (Ruddock, 2003). Uncooled systems are smaller and easier to use than the cooled systems.

TIR data can be digitally enhanced to improve the recognition of anomalies through a variety of standard image processing techniques. None of those techniques were used in this study but we believe that Bob Melia would have used them to improve the recognition of the features he identified in the field. He indicated to us (Bob Melia, personal comm.) that he had made several improvements on the standard processing technology but we are unable to document those methods because of his untimely death.

Appendix 4

Unpublished Thermal Infrared Imaging Reports

Real-Time Thermal Imaging, Inc. possesses at least a dozen unpublished descriptions of Bob Melia's work as project manager done in conjunction with Annette L. Snapp, Ph.D.
The following is a partial list of the project reports that can be made available upon request. Also included in this section are selected newspaper reports documenting some of Bob Melia's work.

1. Archaeological and infrared thermal imaging investigation of cemeteries at Bristoe Station Battlefield, Prince William County, Virginia. Project manager: Bob Melia, Professional archaeologist: Annette L. Snapp, Ph.D. June 2001.
2. Archaeological interpretation of possible features at Hopewell Presbyterian Church and Cemetery, Huntersville, NC. Project manager: Bob Melia, Professional archaeologist: Annette L. Snapp, Ph.D. March 2001.
3. Archaeological interpretation of possible features at Torance House and Store, Huntersville, NC. Project manager: Bob Melia, Professional archaeologist: Annette L. Snapp, Ph.D. March 2001
4. Archaeological interpretation of possible features at Rural Hill, Huntersville, NC. Project manager: Bob Melia, Professional archaeologist: Annette L. Snapp, Ph.D. March 2001.
5. Archaeological interpretation of possible features at Charlotte Museum of History and Hezekiah Alexander Homesite eastern portion Charlotte, NC. Project manager: Bob Melia, Professional archaeologist: Annette L. Snapp, Ph.D. March 2001.

6. Archaeological interpretation of possible features at Latta Plantation, Huntersville, NC. Project manager: Bob Melia, Professional archaeologist: Annette L. Snapp, Ph.D. March 2001.
7. Archaeological interpretation of possible archaeological features at Fort Dobbs historic site, Iredell County, NC. Project manager: Bob Melia, Professional archaeologist: Annette L. Snapp, Ph.D. February 2002.
8. Archaeological interpretation of possible archaeological features at Historic Brattonsville, York County, SC. Project manager: Bob Melia, Professional archaeologist: Annette L. Snapp, Ph.D. February 2002.

Newspaper Reports

[Editorial]. "Remnants of Our Past: Bob Melia Looks at Rowan History," *Salisbury Post* (Feb. 22, 1998).

[Editorial]. "Straight Line to the Past: Probing Rowan's Civil War History," *Salisbury Post* (March 23, 1998).

[Editorial]. “Building a Future,” *Salisbury Post*, (July 26,1998).

[Editorial]. “Connections?” *Salisbury Post*, (July 28, 1998).

“Bounds of New Technology are Limitless,” *Salisbury Post* (Feb. 22, 1998).

"Most People Want to Know About Prison," *Salisbury Post* (July 23, 1998).

"Space-Age Technologies Study History." Popular Science. Website version: http://popularscience.com/scitech/features/salisbury/sal2.html. Viewed, March 30, 2000.

"Study: Prison Larger Than Thought," Salisbury Post (March 20, 1998).

"Thermal Imaging Expert Begins Search for Civil War Sites," *Salisbury Post* (March 18, 1998).

Vita

Raymond Heitger III was born on May 10th, 1968 in Toledo Ohio to Raymond and Betty Heitger. Nicknamed Duke since birth, he has been playing jazz music professionally since the age of twelve. Before moving to New Orleans for the music business he obtained the Degree of Bachelor of Science in Geology from the University of Toledo in 1991. Since that time he has become very busy on the international jazz scene, performing and recording around the world with a diverse roster of musicians. When not on the road, he can be found leading his own Steamboat Stompers aboard the Natchez Steamboat daily. He has attended the University of New Orleans in pursuit of the Degree of Master of Science in Geology since 1992.