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THERMAL INFRARED IMAGERY IN URBAN STUDIES*

BY

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THERMAL INFRARED IMAGERY IN URBAN STUDIES

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September, 1968

In recent years, increasing interest has been shown in remote sensors as devices for investigating urban phenomena, and the utility of a number of these sensors has been clearly demonstrated.[1] The imagery examined was generated by an infrared scanning system operating in the 8-14 micron region, and is discussed here in terms of its potential role as a data source for urban studies. To date, usage of systems measuring thermal emissions has been confined almost exclusively to military use. Consequently, this paper should not be regarded as more than a preliminary investigation of the potential of thermal IR systems in urban research.

Detection and Measurement of Infrared Radiation

All variations in the amount of radiation emitted by various components of the urban area (both man-made and natural) are traceable to differences in either emissivity or temperature, or combinations of both. Emissivity is a basic physical property of objects, and has been defined as the radiant energy emitted per second per cm^2 of surface area. (Simon, 1966)

In the urban environment, there are several ways in which radiant energy is emitted. First, solar insolation may be absorbed by objects and later emitted. Second, sources of non-solar radiant energy such as burning waste heaps, or slag piles and smokestacks may emit directly into the atmosphere.

Third, radiant energy which is non-solar in origin (furnaces, stoves, machines, etc.) may be produced and emitted after conduction through materials. A final consideration is that for solid, non-transparent substances, the sum of reflectivity plus emissivity is unity; therefore every surface in the urban area reflects a certain amount of radiation from its surroundings which, when combined with the amount emitted, determines the radiometric temperature of the surface.[2]

Surface temperature variations are induced by many factors including combinations of the following:

1. Heat capacity of objects
2. Thermal conductivity of objects
3. Surface to volume ratio of objects
4. Surface composition of object (e.g., texture, pigmentation)
5. Angle of incidence of object surface with energy source
6. Radiant energy history (solar history, non-solar history) of area
7. Weather history of area, particularly with respect to such factors as
   a) wind
   b) sky cover and its effect on radiation exchange
   c) dewfall and precipitation

In addition to the sources of surface temperature variation outlined above, the measurement from airborne platforms of radiation emitted from earth surfaces (natural and man-made) is influenced by the atmosphere intervening between the surfaces and the recording instrument. Further consideration must also be given to deviations from the vertical line of sight from recorders to emitting surfaces.

It is clear that control problems may arise in a number of ways. For some studies, it may be desirable to discriminate between the effects of solar and non-solar radiant energy. This may not be a simple task. The list presented above contains several factors which provide strong challenges

to the effective establishment and testing of hypotheses concerning the type and quality of urban information which might be extracted from the thermal IR imagery. There are, of course, control problems associated with all remote sensor systems, and many such discussions may be found in the literature.[3] It is likely that as other systems attain greater control, infrared scanning system operations will also benefit, as control problems are frequently common to several remote sensing systems.

Theoretical Usefulness of Thermal Infrared Imagery in Urban Research

Each remote sensing device possesses some advantage over other systems for certain purposes, simply because of the different parts of the electromagnetic spectrum within which each sensor operates. The infrared scanning system utilized in the present study operates in the 8-14 micron range, and the returns registered on the imagery represent thermal emissions. Since the primary purpose of this report is to comment upon some thermal IR imagery made available to the Remote Sensing Laboratory at Northwestern,[4] a lengthy discussion of the relative merits of thermal IR sensors vis-a-vis other systems lies beyond the scope of the present report.[5] However, there are certain pertinent facts (dealing with the role of the thermal IR system in urban research) which can be noted here.

In examining the potential utility of thermal IR systems, it is important to recall that the infrared scanning system is operable both day and night, subject to the control problems outlined above. Hypotheses which are to be tested my be the same for day or night flights, or they may differ, depending upon the situation. In addition, there is a fundamental question which must be raised in structuring research on the use of remote sensors in data collection: *Can the remote sensor provide for the acquisition of data which satisfy the criteria of uniform classification, timeliness and flexibility,*

more rapidly, accurately, or at lower cost, than other available collection methods.[6] Incorporation of remote sensors into urban data collection is justified only if some combination of these demands upon the system evokes a significant positive response.

There are a number of factors which must be considered when preparing the flight plans for such evaluative studies if the capabilities of the remote sensors are to be rigorously tested. This testing should be designed so as to appraise both the relative advantages and limitations of the sensors. With respect to these systems, one factor which must be considered is the performance characteristics of the sensor. That is, over what range is the sensor operable, what are its resolution capabilities, and how are its returns affected by varying weather and climatic conditions. Further, the type of data which it is purposed to generate from the imagery must be specified. Finally, rigorous testing of remote sensors as data sources is dependent upon the existence of alternate data collection procedures. When such procedures for data acquisition do exist, it is far easier to perform a critical evaluation of the capabilities of different sensors, and to determine the relative utility of each sensor for different data acquisition tasks.

The Imagery Used

The imagery discussed below was obtained from a flight over Evanston, Illinois (NASA Test Site 43) on July 1, 1966, using a Reconofax IV scanner. Sensing equipment was activated at 0354 CDT and terminated at 0442 CDT.[7]

Film coverage of one of the seven lines was lost due to system malfunction. Although the north and south edges of each strip, together nearly one-half of the total width, were severely distorted (an inherent characteristic of this imagery), a fifty percent side overlap of each strip provided for usable coverage of most of the site area. Both duplicate negatives and positive print enlargements were available for the study.[8]

References are made throughout the empirical analysis to the entire imaged area. However, due to constraints imposed by the time and money factors, it was necessary to limit the overlay to one flight line. The line selected was number 5, since it contains a wide variety of urban land uses (see Figure 1).

Study Design

The imaged area was known to be urban, so the major remaining task in terms of design was that of organizing the discussion. As the analysis of the imagery progressed, the following categories evolved as a viable means of pattern classification:

1. Transportation network
   a) movement facilities - streets, railways, waterways
   b) terminal facilities - parking areas (auto parking lots and truck depots), marshalling yards
2. Structures - commercial, industrial, residential, institutional
3. Other - recreation areas.

For each element of these categories, the information that can be extracted by visual inspection is noted, with emphasis placed on the role which emission levels (as registered in the imagery) play in the analysis and synthesis. Information here refers to quantifiable measures such as numbers of elements (houses), length of elements (streets), length of boundaries, and areal extent of different types of land use). The role of emission levels received concentrated study in terms of contrasts among different categories, and within elements of the same category, since primary concern here is with the characteristics which termal IR imagery does not have in common with other imagery. Obviously, if these contrast levels are only slightly dissimilar, the useful analysis will be of only limited utility.

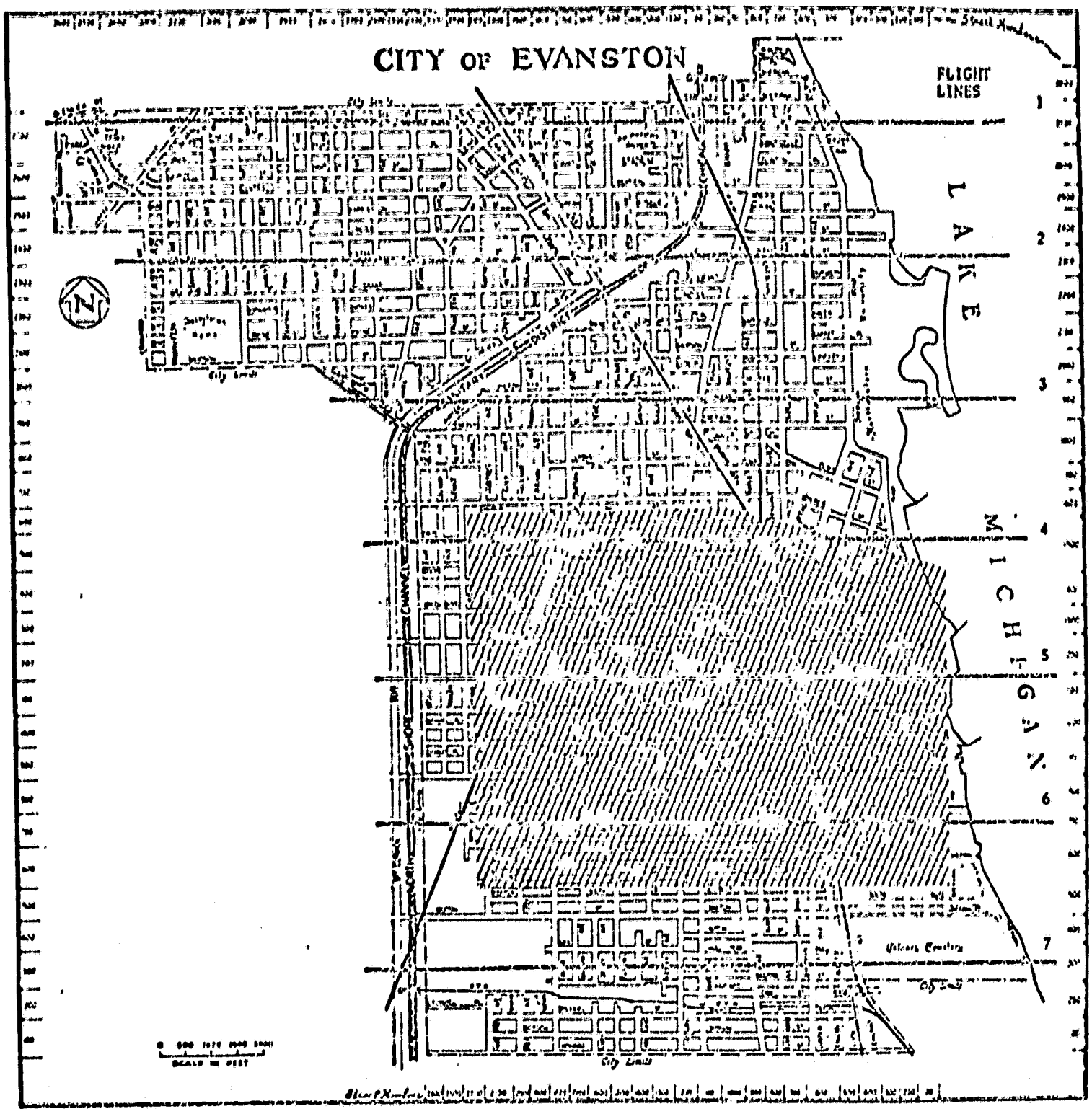


Figure 1. Location Map of Flight Lines, and Area Covered in Figures 2 and 3.

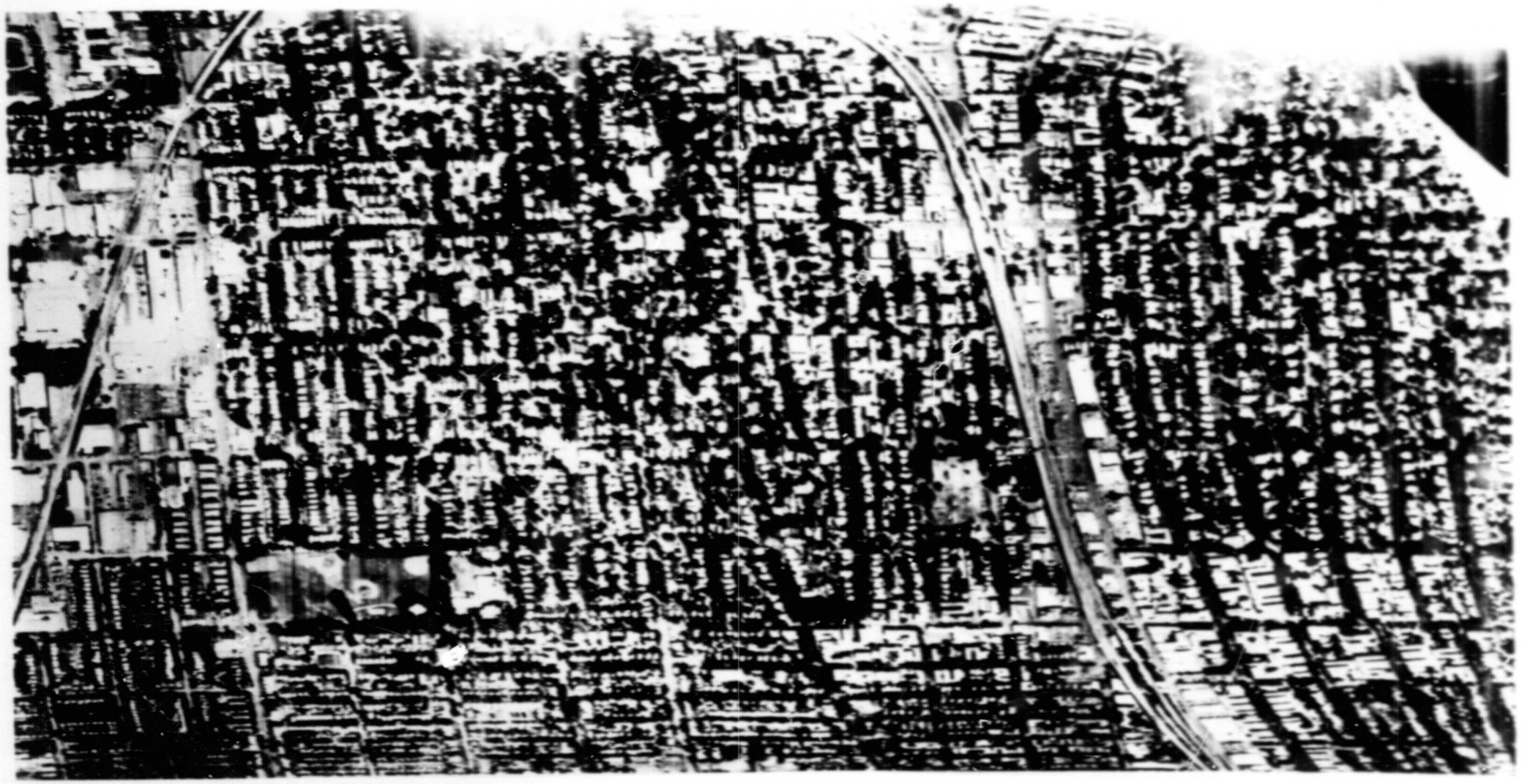
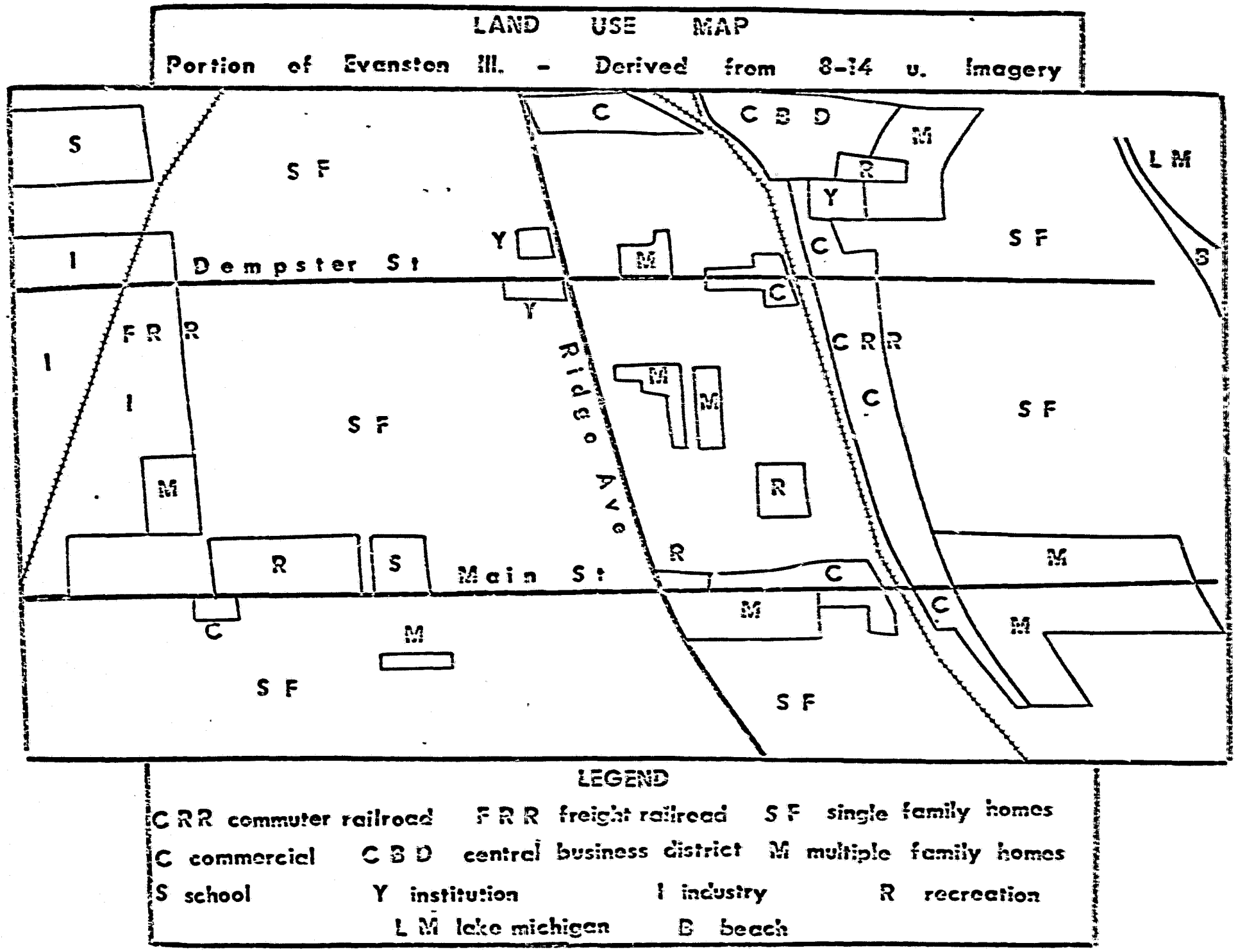


Figure 2. Reconnofax IV Scanner Imagery (8-14u) of portion of Evanston, Illinois.

NASA Earth Resources Program Mission 25, July 1, 1966.

Figure 3.


LAND USE MAP
Portion of Evanston Ill. - Derived from 8-14 u. Imagery
S
S F
C
C B D
M
R
Y
L M
B
I
Dempster St
Y
M
C
S F
F R R
I
I
Ridge Ave
M
M
C R R
C
S F
S F
M
R
R
S
Main St
R
C
M
C
M
C
M
S F
S F
LEGEND
C R R commuter railroad
F R R freight railroad
S F single family homes
C commercial
C B D central business district
M multiple family homes
S school
Y institution
I industry
R recreation
L M lake michigan
B beach

Pre-Analysis Considerations

The approach used in this study to analyze the imagery is similar to that utilized in studying conventional aerial photography, bearing in mind the existence of several important differences. The television type raster resulting from line by line scanning is frequently obtrusive, except in good strips made at the higher altitudes; these obtrustions are frequently distortions of scale caused by imprecise synchronization of film advance with aircraft ground speed and of the angular scanning function.[9] Morgan (1962) further notes that a true thermograph may exhibit strong thermal shadows resulting from the relatively low emission of radiation from cooler, shaded areas. The gray tones in a true thermograph of natural terrain and water surfaces are strictly related to the product of emissivity and temperature, with reflection of the sky or cloud radiation playing a minor role. Even these generalizations must be made with certain reservations, however, because the surface temperature distribution may vary radically in accordance with the local meteorological history.

In addition to local meteorological history, the study of urban area thermographs must also take into account the non-solar generation of radiant energy which will influence the surface temperature distribution of the components of the urban area in a variety of ways.

Empirical Analysis

1. TRANSPORTATION NETWORKS

a. Movement facilities

1. Streets. Identification and mapping of the street pattern is highly correlated with identification of the structures pattern, and the tree pattern. In a number of residential areas tree cover makes it nearly impossible to actually locate the streets, and it must be done by interpolation,

using structures or tree plantings as guidelines. This situation is common in Evanston due to the large numbers of high foliage elm, maple, and oak trees which form a canopy over many of the streets thus precluding direct detection of radiation from street surfaces.

In the Central Business District (CBD) and in areas where strip commercial or industrial structures are located, street identification is straightforward, much as in conventional aerial photography. The linearity of streets, and their grid arrangement are important characteristics. In terms of emission levels, the street pattern contrasts highly with the tree pattern wherever trees do not obscure the streets. On the negative images, streets are gray (cool) and the trees a near-white (warm). In addition, the roofs of a large number of structures, residential, commercial, industrial and institutional, appear near-black (cooler). As a result of these contrasts, it is a relatively simple matter to map the street pattern of the city.

2) Railways. In the area under study, the railways can be identified on the imagery as continuous lines of near-constant return. The railways are darker than the streets in gray tone, with the embankments showing up as thin, white lines along the railways. This is due to dense ground foliage. They differ from the streets in terms of continuity with some streets terminating at the railways, and most streets having intersections. They are not confused with expressways because they are narrower. There are no ramps leading to them from even the larger streets, and most through side streets pass under the railways. On one track, the CTA (Chicago Transit Authority) elevated system, several platforms can be identitied as thin, white strips.

3) Waterways. The waterways in this area consist of Lake Michigan and the upper extension of the Chicago Sanitary Canal. The lake water (warm) contrasts with the beach sand (cool) add the Sanitary Canal (warm) contrasts with its dirt embankments (cool). The canal is large enough to permit pleasure craft boating, but could not handle any large craft. There are no

bridge-raising facilities on any streets crossing over the canal. The only "harbor" facility is the Northwestern University lagoon.

b. Terminal facilities

1) Vehicle parking areas. Auto parking areas located at Dyche Stadium, and the north end of the Northwestern campus behind the Technological Institute, can be readily identified by size, association with large structures, texture, and emission levels. The stadium lot exhibits moderate gray tones on the positive print, and a rough texture suggesting a loosely compacted material. The three campus parking lots exhibit three emission levels centered around the moderate gray of the stadium lot and a very smooth texture suggesting asphalt or concrete. The texture of grass falls between that of the two parking lots, and is slightly less dark than either (higher emission levels). Smaller parking lots at Evanston Hospital and at outlying shopping centers, can also be identified , but not as readily or reliably as the larger ones.

In the CBD, tree cover obscures some of the on-street parking, but several of the larger lots can be easily discerned. Smaller lots and loading zones are indistinguisable. A large number of small features are systematically located on these lots (possibly oil stains) which cannot be identified, making the distinction between the lots and adjacent vacant land containing shrubs very difficult. The parking lot emission levels are slighly higher than those of surrounding buildings and approximate those of street surfaces. Automobiles with running motors show up as hot spots in the lots and streets, but direction of movement cannot be determined from the imagery alone.

Identifiable truck depots are confined to the industrial belt along the railway. In several locations, trucks can be identified in loading zones at the plants. It appears that there are both industrial and warehousing operations here, so that the terminal facilities at the plants serve to load

and unload goods moved by rail and road.

2) Railway marshalling areas. There are two minor marshalling yards in the area. One yard serves the industrial belt, and consists of about seven sets of track. At the time of the flight, three lines of cars were being assembled or disassembled. This yard has a low emission level, and the texture is rough, particularly between the two groupings of track (3 lines and 4 lines). This may be an area which is used for storage of railroad equipment such as rails, ties, barrels, etc. The other yard accommodates railway passenger cars. There are four or five sets of tracks, with the set of tracks which circles the yard showing up clearly. The emission levels here are low, but the texture is not as rough as at the industrial yard. There are cars on all tracks, with most trains consisting of 5 or 6 cars.

2. STRUCTURES

a. Commercial

1) Central Business District (CBD). Identification and mapping of the CBD in thermal IR imagery is similar to working with conventional aerial photography. The size of the buildings, the grouping of such buildings contrasted to surrounding residential structures, the width of the streets, parking lots, on-street parking, etc., all contribute to the identification and mapping of the CBD. The height of these buildings is such that they are not obscured by tree cover, with the result that the CBD stands out as an area containing large segments of low emission and, in some cases, entire blocks of low emission.

One difficulty in mapping the CBD is the determination of those structures which are multi-unit apartment buildings. It is impossible to discriminate between structures which are totally commercial, and those which contain commercial activities on the first or second floors. Trees suggest the demarcation line between commercial and residential structures, but this is not a

completely reliable indicator. Further, parking lots may serve both commercial and residential structures; therefore, they do not preclude the presence of one type of structure in favor of another. As a result, the CBD area, although clearly distinguishable with respect to areas of single family homes, cannot be delimited as to those subareas containing commercial activities exclusively. This is a characteristic of the CBD, and represents a problem common to many photographic studies of the CBD.

2) Strip commercial development. It is possible to identify and map five major areas of commercial strip or string-street development. Including those blocks having more than 50 percent of street frontage in commercial use, the totals are approximately 16 blocks (Central Street) 13 blocks (Chicago Avenue) 7 blocks (Main Street) and 6 blocks (Dempster Street). Field checking produced totals of 18, 13, 7, and 6 blocks, respectively. One noticeable difference among the four strip developments is in the size of a number of structures and accompanying lots along Chicago Avenue. This is an area of automobile dealerships, with each building and lot frequently occupying the equivalent of a city block of street frontage.

The emission levels in these areas closely approximate those in the CBD, but the pattern is elongated along the major traffic arteries, rather than concentrated as it is in the CBD. The approach which was used to identify and differentiate between the structures in the CBD is applicable here. It proved difficult to map the commerical strip development, just as it did with respect to the CBD, in terms of the exact boundary separating it from non-commerical uses.

3) Outlying shopping centers and nucleations. These pockets of commercial activity contrast markedly with the residential environment in which they are located. Size of buildings, adjacent parking lots, and low emission levels are characteristic of such developments.

b. Industrial. Industrial land use is confined to a strip along one

of the railways. The structures are usually large, and terminal facilities are evident for most of the plants. Emission levels are low for all structures. There are several "hot spots" on a few buildings, which may be vents or smokestacks, but positive identification cannot be made. It is not possible to determine if any of the plants were operating (0400 hours) on the basis of emission levels. This may be the result of inadequate resolution, or it may be that the plants are sufficiently well insulated that heat is escaping only through designated outlets.

c. Residential. There are two types of residential structures in this area, single-family homes, and multi-family dwellings or apartment buildings. Single-family homes generally exhibit low emission levels, and contrast with trees, which have high emission levels. In a number of neighborhoods tree coverage forms a canopy, so that house counts could be subject to some error. Individual houses show up clearly, however, where tree cover does not obscure them.

The resolution level is generally inadequate for establishing internal variation within this group in terms of large versus small houses even where the houses are not obscured by trees. Spacings between houses can be determined on the relative basis of some or none for several neighborhoods, with resolution levels and tree coverage being the limiting factors. Variation in emission levels among houses is marginal, and where it does exist, it appears to be largely a function of the quality of the imagery.

Multi-family dwellings or apartment buildings appear very similar to commerical structures, both in appearance and in location. Apartment buildings sometimes have tree-lined walkways separating the wings of the buildings, or their parkways may consist of trees and grass rather than concrete, but the differences vis-a-vis commercial are often minor. Positive identification can be made where walkways are wide and the trees (high emission levels) contrast with the wings of the buildings, for, say, several blocks of development. Isolated structures may frequently be office buildings, and not apart-

ment buildings.

d. Institutional. Land use of this type consists primarily of schools, with hospitals occupying a small portion of the area. Northwestern University appears as a massive complex of large structures, with associated parking and recreation facilities. The buildings with low emission levels are sufficiently high that they are not obscured by the dense tree growth, and contrast markedly with the high emission returns from the trees. Other schools, including Evanston Township High School, are identified by their proximity to athletic fields (football, track, baseball) and playground areas (grassy, and tree-lined). The hospitals could be confused with schools without playground facilities, but extensive parking facilities and ramps point to the structures being hospital complexes.

3. OTHER

Land use in this category which can be identified and mapped is primarily the recreation areas noted above, a large cemetery, parks along the lakefront, a golf course located on each side of the Chicago Sanitary Canal, and a strip of park land along the Canal, south of the golf course. These essentially grassy areas have an emission level which fails below that of the trees and which approximates that of most streets. Most buildings have lower emission levels than the grass-covered areas.

Problems in Utilizing the Available Imagery

In the section entitled, "The Imagery Used", one limitation of the imagery was noted, i.e., the distortion of side edges of each strip. In addition, approximately one-sixth of the total coverage is deficient in gray-tone definition. This may be due to either equipment malfunction or to improper gain adjustment by the operator. Also, severe banding occurred on one run and degraded image resolution of the subject area resulted. Finally, although there is no record of unfavorable atmospheric conditions

in the Flight Data Summary Report[10], or in the ground truth report (see Table 1), some smog or haze may have been present to attenuate over-all image quality.

TABLE 1

METEOROLOGICAL OBSERVATIONS[11]

Time	Station No.	Air Temp. (°F)	Rel. Hum.	Wind Vel.	Cloud Cover	Sky Cond.
0437	1	72.5	86.0	0	0	Clear
0511	8	71.0	86.0	0	0	Clear

Tree cover, a local characteristic which made analysis impossible in some neighborhoods, has already been noted. To repeat, tree cover did not obscure apartment buildings or industrial plants due to the size and height of these structures, but one and two-story residences were completely obscured in a number of locations.

Problems in Utilizing Ground Truth Data

One of the aims of this paper is to attempt to determine the significance of differences in temperature emissions as a means of identifying urban phenomena. In the section, "Empirical Analysis" above, gray-scale values such as white, light gray, black, etc., are used in association with a variety of phenomena to identify the different emission levels present in the imagery. After determining that variation in emission levels aids in differentiating among phenomena, an attempt was made to evaluate more rigorously the degree of possible differentiation.

The ground truth phase of the project was carried out by Texas Instruments and attempted to provide accurate radiometric temperatures at nine ground-test stations (each characterized by a different surface material) at approximately the time of overflight by the airborne sensor. It was expected that the rank ordering of these sites by radiometric temperature would

closely correspond to ranking of these same locations by tonal quality on the imagery; however, there was found to be a very poor relationship between the rank orderings. Subsequent review of the methodology employed by the ground-truth personnel and contracting organization suggests that the final calculated radiometric temperatures used for comparison with the imagery are invalid. The nature of these errors are clarified as follows in the explanation of the ground-truth data collection procedure.[12]

1. On June 29, from 1700 to 1845 hours (CDT), a radiometric temperature T_r (F degrees) of each surface material sample was measured using a Yellow Springs Tele-Thermometer Model 42SF or a Simpson Therm-O-Meter Model 389-3L (for water and sand only). Simultaneously using a Stoll-Hardy radiometer, the radiometric temperature of these same surfaces was obtained for the 8-14 micron range.

2. Utilizing only these data, the emissivity coefficient (e) for the nine surface materials was calculated by the formula, $e^{1/4} = T_r / T_c$ which was derived and modified from the equation representing Stefan-Boltzman's Law:

$$T_r^{\,4} = eT_c^{\,4} + rT_s^{\,4} \qquad (1)$$

where

T_r = surface radiometric temperature in absolute temperature units

T_c = surface contact temperature in absolute temperature units

T_s = sky radiometric temperature in absolute temperature units

e = surface emissivity

r = surface reflectivity

Since the surfaces in question are opaque, e + r = 1; therefore, the following equation for finding e (emissivity) can be derived from Stefan-Boltzman's Law:

$$e = \frac{T_r^{\,4} - T_s^{\,4}}{T_c^{\,4} - T_s^{\,4}} \qquad (2)$$

However, the above is yet a step removed from the equation actually used to calculate emissivity. The ground truth publication on this project states that "although the significance of the sky-temperature influence on emissivity as expressed in the equation above is not fully defined in the practicalities of field measurements on high-emissivity materials, it is generally accepted that the sky-temperature factor can be neglected when measurements are conducted under clear sky conditions and with relatively vertical aspect angles. In this case, therefore, the emissivity factor can be reduced for practical usage to

$$e^{\frac{1}{4}} = T_r / T_c \qquad (3)$$

It should be noted that the above formula which was employed for the calculation of emissivity for all materials can be easily derived from $T_r^4 = eT_c^4$, or simply the Stefan-Boltzman equation without consideration of the amount of energy incident upon a surface at the time of radiometric temperature measurement; in addition, initial radiometric temperatures appear to have been taken in full sunlight. I am of the persuasion that the omission of this factor in the calculation of emissivity for these materials comprises the fundamental error which accounts for the divergence between rank orders mentioned previously.

3. The calculated emissivity values for the nine surface materials were next used to calculate in turn the radiometric temperatures of these surfaces several times a day (including early morning hours) from June 28 through June 30. The surface temperatures of these materials were taken at these times and a corresponding radiometric temperature was calculated for each utilizing equation (3) or:

$$T_r = e^{\frac{1}{4}} \cdot T_c \qquad (4)$$

Since e in all cases is over .90, it is not surprising that all calculated

radiometric temperatures are all a few degrees less than the corresponding surface temperature.

Several points of contention can be found concerning the methodology employed in this phase of the project. Primarily they involve the practice of calculating, rather than directly measuring with the Stoll-Hardy radiometer, the radiometric temperatures of surfaces at the time of overflight. Research involving thermal IR imagery is faced with a number of unknowns, as suggested by the number of control parameters listed previously. Every effort should have been made to design ground truth procedures so as to minimize these errors. Had radiometric temperature been directly measured during the time of overflight, the problem of surface reflectivity would not have entered into the calculations as a possible source of error.

Another weakness concerns a second data collection procedure. There is a lapse of 44 minutes from the first measurement to the last (0437 to 0521), a sufficiently long period of time to affect readings and thereby reduce comparability. In addition, flights over the area commenced at 0354 and ended at 0442 (lapse of 48 minutes), or almost a full hour before ground truth operations began. Any analysis is forced to assume constant cooling of all surfaces during this period. The first lapse was due to a limited supply of testing equipment, as noted by Texas Instruments[13], a situation which should be rectified in future studies if a critical analysis of the imagery is desired. The second lapse between the commencement of flight and ground operations suggests poor co-ordination in programming the project.

Additional criticism might be offered in regard to the limited number of testing stations and the lack of information about such surfaces as roofs of commercial, industrial, or residential buildings. Future studies should incorporate a much wider sample of surface materials. A further weakness lies in the location of testing stations. In an area where a large body of water is likely to influence the humidity content and movement of air in varying

amounts as distance from the water body increases, the locations of test stations should be selected on a stratified basis. For example, all stations could be located 100 yards, 1 mile, two miles, etc. from the shoreline. In this way it might be possible to reduce or eliminate another potential source of error.

Calculation of Emissivity and Radiometric Temperature:

As stated previously, the findings listed in the ground truth publication in regard to calculated emissivity levels and calculated radiometric temperatures appear to be open to serious question. The following is a more detailed critique of the methodology employed in obtaining these values. The following table shows the relevant data pertaining to three of the nine surface materials. The tone values of sand and water represent the extreme range of temperature differences with sand (presumably) having a very low radiometric temperature and water, very high relative to all other surface materials. Old concrete falls between these two.

TABLE 2

COMPARATIVE RADIOMETRIC TEMPERATURES FOR WATER, CONCRETE, AND SAND

	Tone Ranking	T_r Ranking	Calculated e	Calculated T_r	Measured T_c
Water	1	2	.972	69.5	73.0
Concrete	2	1	.964	75.0	80.0
Sand	3	3	.937	56.0	64.5

It is very difficult to explain the striking differences between rankings since (1) the calculated radiometric temperatures vary by several degrees and (2) the tone differences among the three surfaces were quite pronounced on the imagery: on the positive prints water was near-black; sand, near-white; and concrete, gray.

Although the emissivity values of the nine diverse materials were all calculated to be in excess of .93, Professor Morgan of the University of Michigan states that the emissivty of water approaches that of a black-

body (in excess of .95), but most natural surfaces range above .7 and man-made surfaces will usually fall below .7 all along the electromagnetic spectrum (Morgan, 1962, p. 54).

Interestingly enough, other findings published in the same ground truth report, which pertain to ground truth for multispectral photography in the .38 through the 1.1 micron range, appear to support Professor Morgan's estimates and to contrast with the calculated emissivity values. Using an Instrumentation Specialties Company Model SR spectroradiometer, and calculating a ratio between incident and reflected energy, a spectral reflectance coefficient was obtained for each of the eight solid surfaces. At the 1.1 micron level, the reflectivity of various surfaces ranges from .076 for an oiled gravel parking lot to .416 for beach sand. Utilizing the simple equation, reflectivity plus emissivity equals unity, we can assume that the emissivity levels of these surfaces are the reciprocals of their respective reflectivity values. Although it may be questioned whether values established at 1.1 microns will hold for the 8-14 micron range, it is clear from the published ground truth data that the spectral reflectance of these materials is nearly constant for the range .7 through 1.1 microns;[14] Morgan (1962) also suggests little variation throughout the range.[15] It therefore would not seem unrealistic to hypothesize emissivity values for the 8-14 micron range approximately equal to those encountered in the .7-1.1 micron range.

The table on page[22] offers values for radiometric temperatures based not on the calculated emissivity coefficients presented by the ground truth publication, but on a calculation using the reciprocal coefficient of those suggested for surface reflectivity at 1.1 microns. There is one exception, water, for which the calculated emissivity coefficient is considered to be valid since being a virtual blackbody, emissivity can be determined without consideration of reflectivity factors. A Spearman's rank-order coefficient is calculated to show the relationship between rankings based on image tone quality and recalculated radiometric temperature.

TABLE 3

REVISED RADIOMETRIC TEMPERATURE CALCULATIONS*

	Published Emissivity	Reciprocal of Reflectivity	Contact Temperature 0437-0521 hrs.	Recalculated Radiometric Temperature	Recalculated and Interpretive Ranks** #1	#2
Dirt Road	.976	.654	76.0°	22.0	7	7
Gravel Parking Lot	.956	.802	78.5°	49.6	4	3
New Asphalt Parking Lot	.968	.851	83.0°	61.6	3	6
Old Asphalt Parking Lot	.964	.773	78.0°	44.5	5	7
Beach Sand	.937	.584	64.5°	-1.5	9	8
Old Concrete Street	.964	.668	80.0°	28.2	6	2
Oiled Gravel Parking Lot	.976	.924	79.5°	69.0	2	4
New Concrete Street	.968	.545	78.0°	2.3	8	5
Water	.972	--	73.0°	69.5	1	1

*Since contact temperatures and IR imagery were taken at night, surface reflectivity is considered to be negligible. Therefore, in this case equation (4) is used for the calculation of radiometric temperature. However, it should be noted that this equation is not used for the determination of values for $e^{\frac{1}{4}}$. For this recalculation, the values for $e^{\frac{1}{4}}$ are found by using the reciprocal of reflectivity (to the ¼ power) at 1.1 microns.

**Ranking #1 is based on recalculated radiometric temperature (col. 4), ranking #2 is based on emissivity levels registered on imagery. The Spearman rank order coefficient for these rankings is .63. The previous rank order coefficient derived from original ground truth was less than .20.

Some Comments on Previous Thermal IR Research

A literature search has indicated that urban scientists involved with thermal IR imagery (8-14 micron region) have not been explicit about what they want to do, nor the type of imagery desired. This may partly be a result of 1) more rapid progress in research and development using other remote sensing systems; if most existing data needs were being met by these systems, the lag time between availability of the IR system and consideration of the system might be long; 2) lack of familiarity with the workings of the IR system and the content of IR imagery, 3) degraded or poor quality imagery with which scientists have had to work, or 4) less than vigorous thinking by scientists as to potential applications of thermal IR imagery of urban areas.

The following discussion of suggested uses of thermal IR imagery is intended to illustrate that some scientists to date have been somewhat uncritical when evaluating the evaluating the potential of this type of sensor.[16] (A point to be made here is that relatively few scientists appear to have had thermal IR imagery available). Although only two statements from one report, and one from a second are discussed, they are of significance, simply because the application of thermal IR systems to urban areas is in its embryonic stages.

One researcher remarked that "if we consider that roads carrying a greater flow of vehicular traffic have a higher temperature than roads with flow considered normal, and if methods of simultaneous imagery were accomplished so that an area-wide pattern could be established, it might be possible to obtain valid information about mass traffic migrations within a given area on a round-the-clock basis." (Estes, 1966)

There are several aspects of this remark which are suspect. First, with respect to traffic volumes and densities, the friction of tires and the passing of vehicle motors will heat the road, but the amount of

radiant energy generated is unknown. Second, solar insolation heating the road surface will be interrupted as cars pass over the surface, varying from lane to lane as traffic volumes and densities vary from lane to lane, and over time. Third, the role of wind created by the moving traffic will vary with air temperature, with the effect of the vehicle and vehicle motor heat, and with the frequency of vehicles passing over the surface. Fourth, emission levels of a road surface of the same material will be imaged differently if road backgrounds differ since relative emission levels are recorded. Fifth, the absorption and emission capacities and rates differ for materials in terms of composition, age, and angle of incidence with the sun. Sixth, "normal" traffic flow varies with time of day, day of week, season, etc., and is very difficult to measure even at ground level. It would be even more tenuous to estimate normal traffic flow on thermal IR imagery and then compare "normal" emission rates with the emission rates of other sections of road.

A more important, though basic consideration which must be discussed has already been noted in the section, "Theoretical Usefulness of Thermal Infrared Imagery". Namely, is this system to a) provide a new way of collecting data to be incorporated into an already existing data set, of b) is it a way to collect new data? It appears that the suggested use is not addressed specifically to either a) or b); if a), there is no mention of the relative advantage of the data collection method over others in terms of efficiency or accuracy. *The Highway Research Record*, No. 109 (1966a) and No. 142 (1966b) illustrate how researchers do in fact collect a variety of traffic data for a variety of uses. Strip photography using black and white film is being used by a number of highway agencies to collect traffic flow data, and traffic counters provide much of the other required information. Also, cameras are being used in a number of cities to collect such data. As evidenced by this report, thermal IR imagery can provide a basis for

generating data during the hours of darkness when conventional camera systems cannot, but some objective must be specified in order to determine if the experiment is justified. IR imagery may be a useful source of traffic data for the hours when evening traffic flows are heavy; however, this will depend not only on the hypothesis which the scientist wishes to test, but also on the development of estimates of the control parameters noted earlier.

A second remark in the same report suggests that "information on building materials could be obtained using an airborne IR system. Types of insulated roofing materials could be evaluated as to amount of reflected energy and mapped as to distribution." One problem with this suggestion is that 8-14 micron sensing devices measure total radiometric temperature, of which reflected energy is only a small portion. Reflected energy registers on the imagery if the reflected energy from one surface is absorbed by a second surface and later emitted, but the amount can only be determined in controlled experiments. In addition, there are a number of factors which influence the appearance of insulating material in conventional aerial photography where reflectivity is measured, and in thermal IR scan imagery where emission levels are measured. It appears that much more experimental work is required in the analysis of material reaction to energy if we are to understand the contents of the imagery and begin work at the aggregate level.[17] A start has been made in this direction, and suggestions have been made as to future avenues of research.[18]

The second report referred to here is concerned with the possibility of isolating during electronic processing of thermal IR imagery, those radiation levels above or below a selected intensity level. The observations, pertaining to imagery of a small urban development conclude by stating that "although line-scan imagery is not as suitable for detailed mapping as is conventional (aerial) photography, it is felt that the gross measurements usually performed as a first step in land utilization and terrain studies

would be greatly facilitated by the use of line-scanning reconnaissance systems." (Ory, 1965) It is an accepted fact that machines perform a number of photographic operations more quickly and more accurately than the human analyst or interpreter. However, the use suggested here does not appear to justify a thermal IR system. First-generation land use studies are usually very simple and straightforward, and can be easily performed by an interpreter. In addition, speed is not always of the essence in first-generation land use studies, with more emphasis being placed on accuracy, and the locating of anomalies in the general land use pattern. Finally, the scale distortion usually present in scan-line imagery would make accurate area measurements virtually impossible. As a result, even low resolution conventional aerial photography would be preferable. On the basis of those arguments, the suggested use in Ory's paper appears unwarranted. The automatic separation of imagery is a very appealing operation, but not for the reasons given.

Implications for Future Studies

There appear to be three basic factors involved in the development of thermal IR research. First, there appears to be no design to current experiments.[19] If hypothesis are to be tested on the basis of data extracted from thermal IR imagery, it is necessary that experiments be conducted only after a specific design has been prepared.

Second, the available imagery appears to be of inferior quality in terms of extracting data meaningful for urban research. Imagery must be made available which is of markedly higher quality than any we have seen to date if anything more than gross land use mapping is to be done. Further, in order to evaluate the contents of thermal IR imagery, comparable sets of

imagery from different remote sensing systems must be simultaneously made available to researchers.

Third, there is a particular need for heavy investment in ground truth measurements, particularly with respect to interaction between matter and energy. Experiments will have to be carried out so that the nature of the control parameters discussed previously can be thoroughly investigated, and estimates established.

This paper demonstrates that a variety of urban data can be extracted from thermal IR imagery. However, it is possible to collect very similar data from conventional aerial photographs. The utility of thermal IR imagery cannot be fully tested until the three basic conditions of project design, comparable sets of imagery, and ground control leading to estimates of control parameters for the different systems, are taken into account and satisfied.

NOTES

1. See for example, Branch (1948), Highway Research Board (1966a, 1966b), Manji (1968), Moore (1968), Marble and Thomas (1966), and Wellar (1967, 1968a, 1968b).

2. See also Morgan (1962, p. 52).

3. An overview of a number of studies is provided by Leonardo (1964), and Moore and Wellar (1967).

4. Contract No. 14-08-0001-10654, Geographic Applications Program, U.S. Geological Survey, National Aeronautics and Space Administration.

5. Morgan (1962, p. 57) states that at levels of current technology, only remote sensors with "photoelectric detectors combine the sensitivity and speed of response for highspeed measurements from an aircraft."

6. These suggestions appear to be applicable to all operations which propose to use remote sensors as devices for data generation activities.

7. See Reference 13 for more details.

8. The resolution level of the imagery cannot be released in this report, but the reader can determine what has been called "ground resolution level" from the imagery using standard photogrammetric techniques.

9. See Morgan (1962) for more details.

10. National Aeronautics and Space Administration (1966).

11. See Reference 17 for source of data.

12. Ibid, p. 28.

13. Ibid, p. 30.

14. Texas Instruments Inc. (1965), see Figure 18, p. 25.

15. Morgan (1962, p. 54).

16. Similar arguments can be found in Wellar (1968b).

17. See Legault and Polcyn (1964) and Schneider (1967).

18. See Holter and Legault (1964).

19. The responsibility of this writer was to determine those urban data extractable from thermal infrared imagery. It was established that at the given resolution level, thermal IR imagery could be made to yield urban data. The utility of these data remains to be determined.

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