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AERIAL THERMOGRAPHY
FOR ENERGY CONSERVATION

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SUMMARY

Thermal infrared scanning from an aircraft is a convenient and commercially available means for determining relative rates of energy loss from building roofs. The need to conserve energy as fuel costs have risen has made the mass survey capability of aerial thermography an attractive adjunct to community energy awareness programs. Prospective users are provided with background information on principles of aerial thermography, thermal infrared scanning systems, flight and environmental requirements for data acquisition, preparation of thermographs for display, major users and suppliers of thermography, and suggested specifications for obtaining aerial scanning services.

INTRODUCTION

The National Energy Plan (NEP), announced in April 1977 by President Carter, focuses attention on United States energy policies and planning. A major objective within the NEP is to reduce energy-demand growth from the historical 3 percent per year to 2 percent per year in several ways, including energy conservation in all sectors. It has been proposed that 90 percent of U.S. residences and commercial buildings be insulated by 1985 to help fulfill this objective. Adequate insulation could save approximately 4 million equivalent barrels of oil per year for every million buildings insulated. The application of an efficient mass surveying technique can create a public awareness of energy conservation and thereby catalyze cost-effective energy conservation actions.

A technique that has proven very useful over the past 3 years as a mass surveying tool for detecting energy losses from building roofs is thermal infrared scanning from an aircraft. It is a convenient means of surveying a large number of buildings, and the results provide synoptic thermal maps showing the relative thermal energy loss rates of each building roof surveyed.

To illustrate - NASA conducted an aerial thermography program for energy conservation purposes during the 1974, 1975, and 1976 heating seasons at all its field centers (ref. 1). Energy losses from building roofs, central-heating-system distribution lines, building ventilators, and heated steps and sidewalks were detected. Estimated first-year savings were \$480 000 at a cost of \$94 000 for a 5-to-1 payback on initial investment. Similar results have been obtained by other major users of aerial thermography.

This document provides prospective users with the basic information required to plan an aerial thermography program for their unique needs. Discussed in a general way are

- (1) Principles of aerial thermography
- (2) Thermal infrared scanning systems
- (3) Data acquisition requirements
- (4) Preparation of thermographs for display
- (5) Cost of aerial thermography
- (6) Major users and suppliers of aerial thermography
- (7) Recommendations and conclusions
- (8) Proposed specifications for aerial thermography

References 1 to 7 cover a variety of aerial thermography applications in more detail.

PRINCIPLES OF AERIAL THERMOGRAPHY

The use of aerial thermography for detecting relative energy losses from building roofs involves the application of thermal infrared radiation technology. The foundation of this technology is the Stefan-Boltzmann law relating the rate of total energy emitted by an object W to its absolute surface temperature T in degrees kelvin:

$$W = \epsilon\sigma T^4$$

where ϵ is the graybody emittance of the surface - a nondimensional coefficient with a value between 0 and 1 - that represents a surface's efficiency in radiating energy; and σ is the Stefan-Boltzmann constant, with a value of $5.67 \times 10^{-12} \text{ W cm}^{-2} \text{ K}^{-4}$. Thus, since the energy loss through a surface is associated with the surface temperature, a technique that measures the surface temperature can also be used to detect the relative rate of energy loss.

All materials with temperatures greater than absolute zero continuously emit thermal infrared energy in amounts depending primarily on the temperature of the material. The location of the thermal infrared spectrum within the general electromagnetic spectrum is shown in figure 1. It lies between the visible and microwave spectrums and has associated with it wavelengths ranging from 0.7 to 1000 micrometers. In particular, the enlarged view (right side of fig. 1) shows that the radiation of interest for thermography ($T \approx 300 \text{ K}$) is associated with wavelengths of about 10 micrometers.

This relationship is shown more precisely in figure 2, where the amount of thermal infrared energy emitted is given as a function of wavelength and blackbody ($\epsilon = 1.0$) temperature. These blackbody radiation spectra were derived theoretically by

Max Planck and form the basis for thermography. These curves are also useful for determining the radiation spectrum of interest for emittances of less than 1. In this case, where ϵ is less than 1.0 and is constant over the wavelength range of interest (a graybody), the curves of figure 2 must be lowered by the value of the emittance. For example, most roofing materials are approximate graybodies with an emittance of about 0.9; therefore, the ordinate values of each curve in figure 2 must be multiplied by 0.9 to obtain the appropriate curves for roofing materials. Also, since building energy losses are associated with temperatures of approximately 300 K, scanning for energy loss detection must be in the 4- to 20-micrometer wavelength range (fig. 2).

A variety of detectors are available that operate in the thermal infrared wavelength region. The relative spectral response of a typical detector (mercury-cadmium-telluride) is shown in figure 3, along with three other responses for reference. Normally, detectors operating at the longer wavelengths must be cooled to liquid-nitrogen temperatures (~ 70 K) to obtain good signal-to-noise ratios (lower part of fig. 3).

Now that the wavelengths associated with a practical detector for thermal scanning are known, another aspect that must be considered is the effect of atmospheric absorption. Many atmospheric gases - in particular, water vapor and carbon dioxide - absorb radiation in the infrared region. Therefore thermal scans cannot be made effectively at any wavelength but must be made where the atmosphere is relatively transparent to such radiation. The atmospheric absorption effect is shown in figure 4. The atmosphere transmits thermal radiation efficiently at 11 micrometers but does not transmit at 7 micrometers. For this reason, the remote detection of thermal energy radiation from building roofs is generally in the 8- to 11-micrometer wavelength range, where the atmospheric transmittance is high.

In summary, the amount of thermal energy emitted from a surface depends on the energy balance between the surface and the surrounding environment. This energy can be detected by an airborne infrared scanning system. When the amount of energy being lost through the roofs is excessive, such information may induce building owners to take energy conservation measures.

THERMAL INFRARED SCANNING SYSTEMS

Simplified block diagrams of infrared scanning systems currently in use are shown in figure 5. Energy from viewed objects is collected by the scanner optics and focused on a detector that is sensitive to radiant energy in the 8- to 14-micrometer wavelength region (fig. 2). At the detector, an electrical signal is generated that is directly proportional to the emitted energy flux level of the sensed radiation. This signal is then amplified greatly. At this point, the signal can be processed further in

one of three modes (1, 2, or 3 in fig. 5(a)). The most commonly used processing mode (1 in fig. 5(a)) is for the signal to drive a light-emitting diode like those in a calculator display. The diode light is focused on ordinary black-and-white photographic roll film and is slaved to the scanning mirror so that it exposes the photographic film just as the scanning mirror surveys the terrain. After exposure, the film is developed in a standard photographic laboratory and enlargements are printed. The imagery obtained by this mode is continuous in tone and normally can provide 6 to 10 calibrated density levels (or gray tones) that correspond to various surface temperatures.

The second processing mode (2 in fig. 5(a)) takes the signal from the amplifier, inputs it to an analog-to-digital converter and records the resulting digital data on high-density digital tape (HDDT). The recorded digital data are subsequently fed into a ground-based minicomputer processor to display and produce the imagery required (fig. 5(b)). This processing mode is extremely versatile and permits a wide range of calibrated densities in the imagery as well as arbitrary color coding of the temperatures. Examples of both a black-and-white and color thermograph of the same residential area are shown in figure 6. Color coding makes it easier for the public to understand the temperature information in the imagery. The ultimate user of the imagery can usually discriminate between arbitrarily selected colors although he may have difficulty in discriminating between shades of gray. This machine-processing and color-coding mode can be considerably more expensive than the analog mode primarily because of the minicomputer required and the extra expense of processing the color imagery.

A third infrared scanning mode (3 in fig. 5(a)) that has occasionally been used is discussed here for the prospective user's awareness. This mode employs a scanner with an automatic gain amplifier. The military developed automatic gain scanners for night observations in order to "see" objects with small differences in temperature from their surroundings. On a military reconnaissance mission there usually is but one opportunity to obtain the imagery. Therefore, the signals from every scan line are fed into an automatic gain amplifier to maintain the dynamic range of the imagery constant regardless of the signal strength. Thus, a scanned high-temperature object reduces the amplifier gain while maintaining a constant output, but a scanned low-temperature object increases the gain to achieve the same output. As a result, the density levels in the imagery may vary greatly and are not calibrated relative to each other. What appears at one density level in one part of the imagery is associated with one temperature, but the same density level in another part of the imagery may represent a completely different temperature. Although such a scanning approach may work in fortuitous terrain and environmental conditions, in general, it defeats the objectives of relative energy loss detection from buildings. Such an approach for

determining relative energy loss cannot provide the most useful data.

SCANNER OPTICS

The optics of an infrared scanning system consist of a scanning mirror, folding mirrors, and a set of telescopic optics to give the instantaneous field of view (IFOV) required. Figure 7 is a schematic of a typical system. The rotational speed of the scanning mirror can be varied to match the aircraft's forward velocity and to thus produce continuous imagery. In addition, line scanners normally have some type of internal calibration source (blackbodies in fig. 7) whose signal levels can be printed on the film imagery or recorded on the HDDT, thereby calibrating the imagery.

The most important parameters to consider when evaluating infrared line scanners are those that define its "seeing" ability in terms of the total field of view (FOV); the instantaneous field of view (IFOV), which defines its spatial resolution; and the temperature sensitivity in terms of noise-equivalent temperature (NET). Typical values of these important parameters are an FOV of 110° , an NET of 0.5° C, and a resolution (IFOV) of 1 to 2.5 milliradians.

A typical line scanner sees the ground from horizon to horizon across the aircraft flightpath and builds up an image, line by line, as the aircraft progresses along its flightpath. This process is shown schematically in figure 8. The ground resolution element shown in the figure is associated with the scanner IFOV. For example, a scanner with an IFOV of 1 milliradian that is flown at an altitude of 305 meters (1000 ft) has a ground resolution element 0.305 meter by 0.305 meter (1 ft by 1 ft) at nadir (that point directly beneath the aircraft). At an altitude of 610 meters (2000 ft) the ground resolution element is 0.610 meter (2 ft) on a side. From the standpoint of cost, the resolution required is very important because it determines the amount of area scanned on each flightpath and therefore the number of flightpaths required to scan a given area. Thus, because the scanning system resolution determines the scale of the resultant imagery as well as how long the aircraft has to fly to scan a given area, it affects the cost.

DATA ACQUISITION REQUIREMENTS

How well an aerial thermography program stimulates energy conservation critically depends on the quality of the imagery. From our experience, the ultimate user - the homeowner or the businessman - has several requirements that the imagery must meet to be effective. He must be able to easily locate his building, he must be able to clearly distinguish it from nearby structures (good visual discrimination), and he must be able to easily determine any energy losses from the roof of his building (good

temperature discrimination). If these requirements cannot be met rather easily, the user loses trust in the interpretation of the imagery and is not easily persuaded to enter into an energy conservation program.

The weather conditions at the time of data acquisition are a prime factor in obtaining quality imagery. To eliminate the cumulative effects of solar heating of the rooftops, data are generally obtained between 9 p. m. and well after midnight, when most of the stored solar heat has been reradiated to space. The weather criteria we currently specify for both good temperature discrimination and good visual discrimination are

(1) An ambient air temperature of less than 1.6°C (35°F) (This condition insures that the heat loss is adequate for discerning losses easily.)

(2) Clear skies (This condition insures that the imagery has good temperature discrimination.)

(3) Little haze (Haze reduces the amount of energy a remote sensor "sees" and thereby introduces possible errors.)

(4) A dewpoint at least 2.8 degrees C (5 deg F) below the ambient air temperature (The condensation of water vapor on a surface (dew) tends to mask heat losses.)

(5) Little or no wind (Any wind causes all surface temperatures to approach a common value and thereby masks heat loss. The higher the winds, the more uniform the surface temperatures become.)

To obtain the clearest indication of energy loss, data should be taken late enough at night for the roof to reradiate as much solar energy as possible but before the background cools excessively. In addition, the roofs must be clear of snow and have no standing water. Both snow and water mask energy loss. These generalized criteria for suitable environmental conditions are based on experience; however, they are still being investigated.

The flight altitudes used to obtain aerial thermography are generally from 305 to 610 meters (1000 to 2000 ft). As noted previously, the flight altitude used is a trade-off of the desired resolution of ground objects and the total costs of the overflights and image processing. A good compromise has been an altitude that gives a ground resolution element of approximately 0.19 to 0.23 square meter (2 to 2.5 sq ft). With this resolution element, most thermal energy losses and their locations are easily detected.

PREPARATION OF THERMOGRAPHS FOR USE

The first step in preparing thermographs for use is to select the scale of the final photographic prints to be used in the informational transfer process. Prints then are made by a reliable photographic laboratory. Normally, the prints used are five- to ten-times ($5\times$ to $10\times$) enlargements that yield thermographs with scales from 1:3600 to

1:1800. At the same time, an accurate street map of the community overflown is obtained, and the flight lines are drawn on it. Each print enlargement is then labeled according to the flight line and the print number along the flight line. For example, "3-8" represents the eighth print along flight line 3. An example of such a print is given in figure 6. In addition, each print is annotated with several key streets for good orientation. Finally, the prints are arranged in order along a flight line, and print packages are compiled according to flight-line number. In addition, transparencies (slides - both color and black and white) of special, selected energy loss situations that may be of general interest (e. g. , state buildings, city buildings, schools, and hospitals) are made to be used in public relations programs.

COST OF AERIAL THERMOGRAPHY

Representative costs for obtaining aerial thermography are difficult to assess because of the many variables. Each project is unique. In general, commercial contractors doing aerial thermography do not have a standard pricing schedule since they estimate each project's costs by the imagery products required and the community location with respect to their center of operations.

Two recent thermography projects - one small and one large - are cited to give the potential user a "feel" for costs. The small project was a demonstration program encompassing 67 square kilometers (26 sq miles). The products requested were 70-millimeter black-and-white negatives, 5x enlargements of each negative, and magnetic tapes of the data. Six separate bids were obtained. The bids ranged from \$263 to \$788 per square kilometer (\$680 to \$2040/sq mile). The highest bid was influenced greatly by the overflight location relative to the contractor's location - the personnel/aircraft transmit costs were high. The next highest bid was \$571 per square kilometer (\$1480/sq mile).

The large project is a current statewide effort called Operation Sky Skan that is being conducted in Iowa by the Iowa Utility Association and is managed by Robert G. Barger of the Iowa Public Service Company. The program involves over 800 cities and towns throughout the state and encompasses more than 10 360 square kilometers (4000 sq miles) at a cost of approximately \$42 per square kilometer (\$110/sq mile). The products requested were 70-millimeter black-and-white negatives with 28- by 36-centimeter (11- by 14-in.) photographic enlargements giving a scale of 2.5 centimeter (1 in.) for every 61 meters (200 ft) of terrain.

Both the example projects used black-and-white imagery. The cost of doing the projects with color imagery would have been significantly higher. Based on the few relevant aerial thermography programs that we are familiar with, and which were done with color imagery, it appears that a program using color imagery would cost at

least twice as much as a program using black-and-white imagery. The immediate reaction of a potential user to such a cost disparity is that full-color aerial thermography programs could not possibly be as cost effective as black-and-white programs. However, the validity of such a conclusion can be questioned. If a full-color program were to achieve more response than a black-and-white program, it could be even more cost beneficial. Although the possibility is there, the question has not yet been answered and this remains an area to be investigated.

MAJOR AERIAL THERMOGRAPHY USERS AND SUPPLIERS

There are a number of active aerial thermography programs in the United States. The following incomplete list of program managers may provide the potential user with additional sources of experience and information on major aerial thermography programs being conducted for energy conservation purposes:

Robert G. Barger
Manager, Energy Conservation
Iowa Public Service Company
Orpheum Electric Building
Sioux City, IO 51102
(712) 277-7554

Marsha K. Battles
Minnesota Energy Agency
150 East Kellogg Blvd.
St. Paul, MN 55101
(612) 296-1732

James R. Bjorklund
Division Marketing Manager
CENGAS
113 S. Main Avenue
Sioux Falls, SD 57101
(605) 336-0530

Vern Cimmery
Bonneville Power Administration
830 N. E. Holladay Street
Portland, OR 97208
(503) 234-3361

John R. Jack
Head, Environmental Applications Section
NASA, M. S. 54-2
21000 Brookpark Road
Cleveland, OH 44135
(216) 433-4000 Ex. 5519

David Loos
Manager, Residential Energy Conservation
Illinois Division of Energy
222 South College
Springfield, IL 60706
(217) 782-7500

The following is a partial list of organizations that possess, or have access to, airborne thermal scanners and offer their services commercially for energy conservation purposes:

Abrams Aerial Survey Corp.
124 N. Larch Street
Lansing, MI 48901
Attn: J. Linn
(517) 372-8100

Daedalus Enterprises, Inc.
Applications Division
P. O. Box 1869
Ann Arbor, MI 48106
Attn: A. Arro
(313) 769-5649

Energy Measures Corp.
2808 Longhorn Boulevard
Suite 305
Austin, TX 78759
Attn: W. Hazard
(512) 837-7756

Environmental Research Institute of Michigan
Application Division
Ann Arbor, MI 48106
Attn: D. S. Lowe
(313) 994-1200

ESCA Tech. Corp.
3001 Redhill Ave.
Bldg. 2, Suite 212
Costa Mesa, CA 92626
Attn: M. Gallagher
(714) 751-3630

Mead Technology Laboratories
3481 Dayton - Xenia Rd.
Dayton, OH 45432
Attn: R. Lusk
(513) 426-3111

Photo Science, Inc.
7840 Airpark Rd.
Gaithersburg, MD 20760
Attn: J. W. White
(301) 948-8550

Remote Sensing Institute
South Dakota State University
Brookings, SD 57007
Attn: F. A. Schmer
(605) 688-4184

Texas Instruments, Inc.
Box 5621
Mail Station 949
Dallas, TX 75222
Attn: F. J. Buckmeier
(214) 238-3444

RECOMMENDATIONS AND CONCLUSIONS

The following recommendations and conclusions are made for the guidance of those who have made the commitment to use aerial thermography for energy conservation.

The initial step, and perhaps the most important step that can be taken to implement an effective program, is to seek the advice of those who have managed major programs. These managers, listed in the preceding section, have a wealth of experience in securing a contractor, setting contract specifications, and selecting the imagery and transfer methodology for public relations programs.

A proposed set of specifications is presented in the appendix. These specifications may be used as an initial guide in establishing requirements for future programs.

In conclusion, aerial infrared scanning of residential, commercial, and industrial complexes for remote detection of thermal energy losses has been demonstrated to be a cost-effective way of creating public awareness and providing energy loss information useful for motivating energy conservation action. It is a good first step in a general program to focus attention on the need for energy conservation.

Steps that should be considered to supplement the aerial thermography results are building energy audits and inspections, both of which can be easily implemented with good results. Since such steps can provide accurate supplemental information, they should be planned for and included in every overall conservation program. These steps are so important that including their undertaking is probably sufficient justification for any overflight activity.

APPENDIX - PROPOSED SPECIFICATIONS FOR AERIAL THERMOGRAPHY
TO DETECT ENERGY LOSSES

Scope

Purpose. - Aerial thermography will be acquired to detect energy losses from building roofs and from high-temperature water and steam heating lines both below and above ground.

Work covered. - All plant, superintendence, labor, equipment, and materials required for an aerial survey to detect energy losses and to provide the desired products must be specified.

General Data

Location. - The cities to be surveyed are _____ (to be specified by user).

City descriptions. - The area to be surveyed in each city is delineated by the city boundaries as shown on enclosed maps.

Environmental Conditions

The environmental conditions shall be documented at the beginning and end of each flyover.

Weather. - Overflights shall be made when weather conditions are appropriate for obtaining quality imagery that permits good visual discrimination of structures and good temperature discrimination of energy losses. Mandatory weather conditions are an ambient air temperature less than 1.6°C (35°F), clear skies, calm winds, and a dewpoint spread of at least 2.8 degrees C (5 deg F). There shall be no snow or water on the roofs.

Time. - Data shall be acquired between 9 p. m and 3 a. m, from October 15 to April 1.

Ground Support

All ground support of the overflights shall be supplied by the contractor.

Flight Data

The following data shall be recorded and supplied for each overflight:

- (1) City
- (2) Flight line numbers
- (3) Map of city showing flight lines as flown
- (4) Date and time of beginning and end of each overflight
- (5) Aircraft altitude above ground level for each overflight
- (6) Aircraft bearing for each flight line
- (7) Ground-level ambient air temperature, wind velocity and direction, and dew-point temperature at the beginning and end of each overflight

Quality of Imagery

Data recording. - Data shall be recorded directly from the scanner onto magnetic tapes and/or roll film suitable for postflight analysis (to be chosen by the user). Data shall be calibrated so that relative or absolute radiant energy can be obtained from all structures. Automatic gain systems shall not be used.

Processing. - Taped data shall be transferrable to photographic film or usable for computer processing. Processing shall include a density level slicing that will achieve both good temperature discrimination and good visual discrimination. Processing can result in either black-and-white or color-coded imagery (to be chosen by the user).

Imagery requirements. - The spatial resolution must permit easy identification of individual buildings. Spatial resolution shall be at least 0.76 meter (2.5 ft). In addition, the shape and size of each building must be easily identifiable. Thermal imagery shall be obtained in the 8- to 14-micrometer wavelength region and must be capable of depicting temperature differences as small as 0.5 degree Celsius. The scale of the finished product shall be _____ (to be specified by user) so that the thermographs can be easily interpreted visually without special equipment.

Flight line requirements. - Flight lines shall be so planned by the contractor that the ground coverage of each scan does not exceed a 90° field of view. Adjacent flight lines shall have sufficient side overlap so that a good mosaic of the imagery can be constructed. Flight lines shall be in the same direction and generally parallel to major streets within the survey area.

Reporting

The method used to determine temperature from film density shall be described if black-and-white imagery is used. The temperature range for each color shall be supplied if color coding is used. The overflights and a full description of a representative energy loss situation for each city shall be documented within a specified number of weeks after delivery of the thermography. All reporting shall be completed

in a specified number of weeks after completion of each aerial survey. All flight data, data tapes, and imagery negatives shall be provided with the report.

REFERENCES

1. Bowman, Robert L.; and Jack, John R.: Application of Remote Thermal Scanning to the NASA Energy Conservation Program. NASA TM X-73570, 1977.
2. Goldstein, Richard J.: Application of Aerial Infrared Thermography to the Measurement of Building Heat Loss. ASHRAE Trans., vol. 84, part 1, 1978.
3. Sampson, Robert E.; and Wagner, Thomas W.: Applications of Infrared Technology to Buildings. Proc. of the Third Biennial Infrared Information Exchange. AGA Corp., New Jersey, 1977, pp. 89-97.
4. Brown, R. J.: Infrared Scanner Technology Applied to Building Heat Loss Determination. Can. J. Remote Sensing, 1977, p. 78-10112.
5. Bjorkland, J.; Schmer, F. A.; and Isakson, R. E.: Aerial Thermal Scanner Data for Monitoring Rooftop Temperatures. (SDSU-RSI-75-11, Remote Sensing Inst., S. Dakota State Univ.; NASA Grant NGL-42-003-007.) NASA CR-145747, 1975.
6. Aerial Infrared Users Manual. MEA DOE Contract EC 77 C02 4161-3 and RMI DOE Contract EC 77 C01 8668, Minnesota Energy Agency and Remote Sensing Institute, 1978.
7. Bowman, Robert L.; and Jack, John R.: Aerial Thermography for Quantitative Heat Loss Determinations. NASA proposed Technical Memorandum.

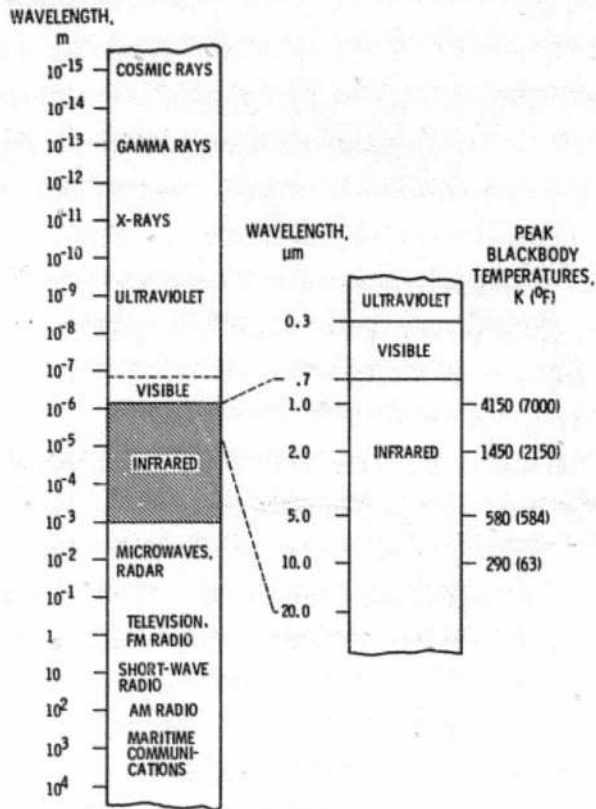


Figure 1. - Electromagnetic spectrum.

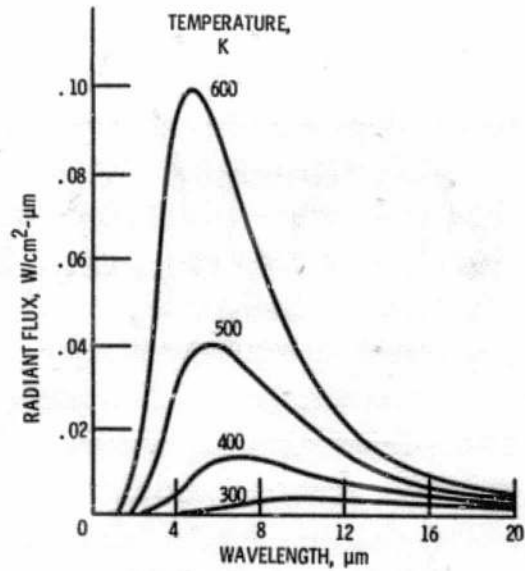


Figure 2. - Blackbody radiation spectra.

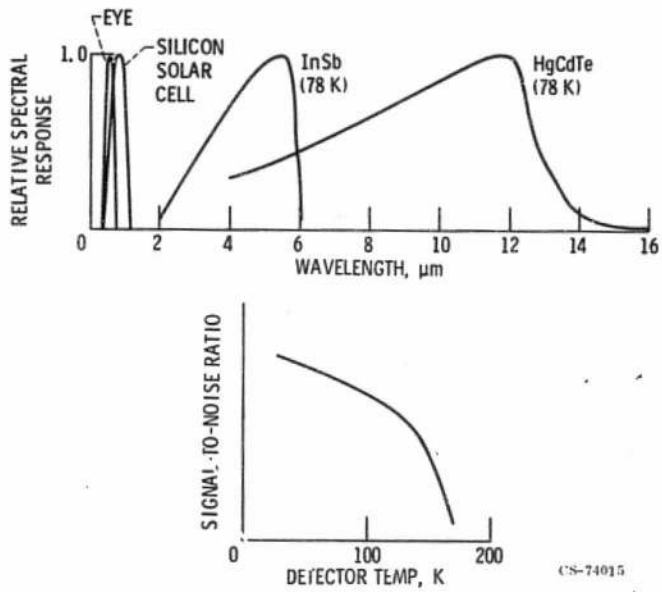


Figure 3. - Detector response characteristics.

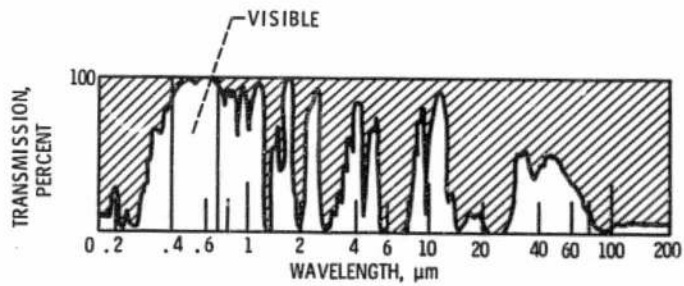
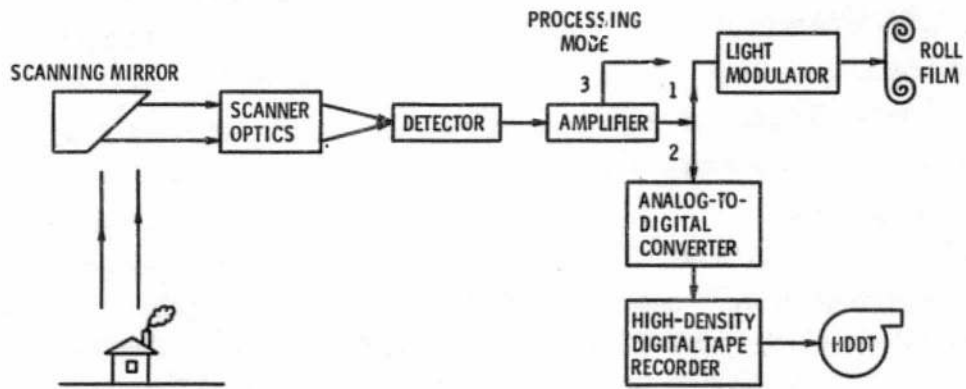


Figure 4. - Atmospheric transmission spectra.

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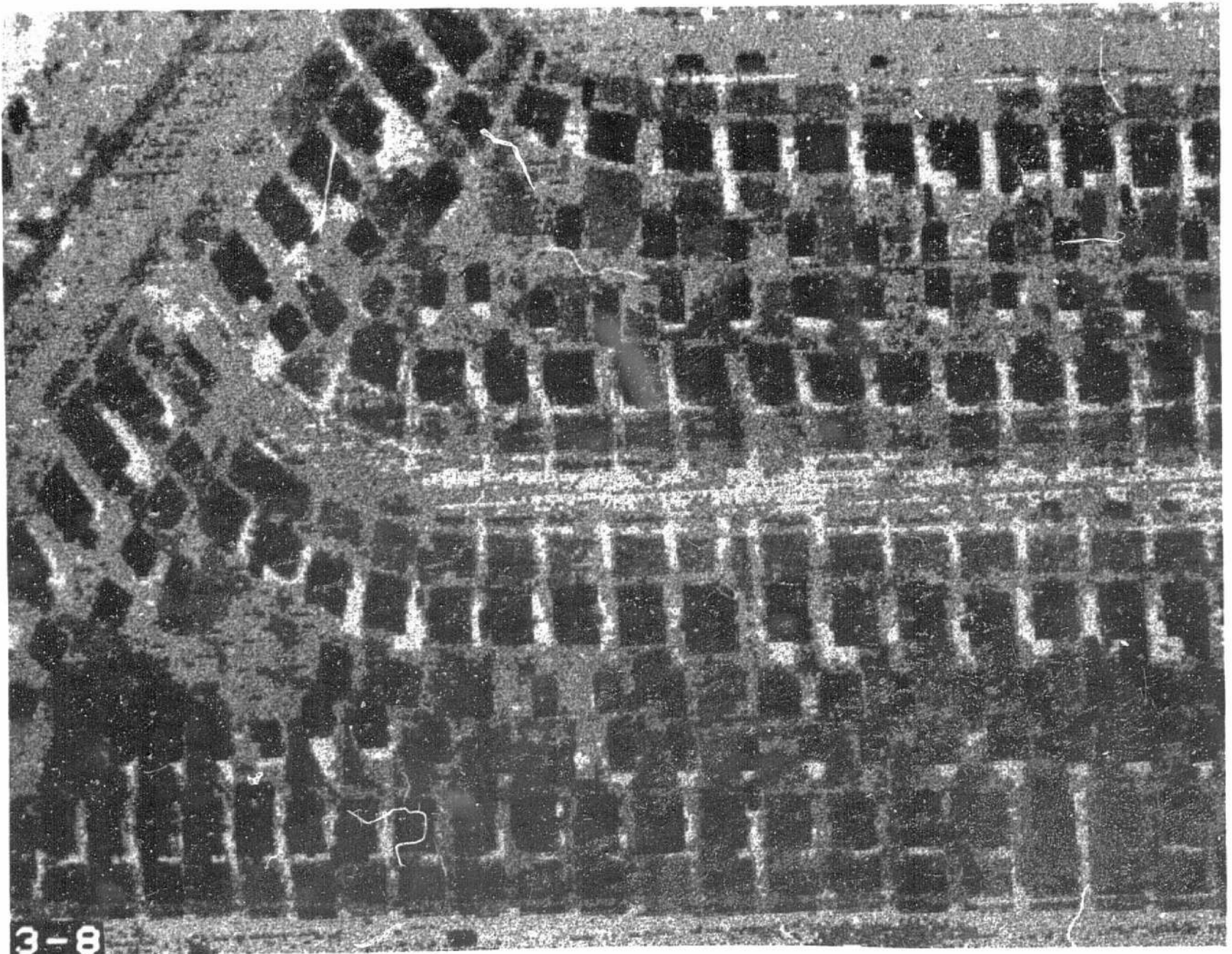
(a) Airborne sensing system.



(b) Ground-based processing system.

Figure 5. - Infrared scanning systems.

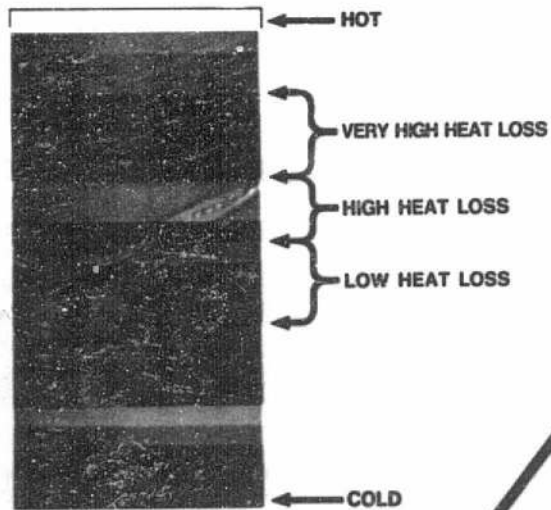
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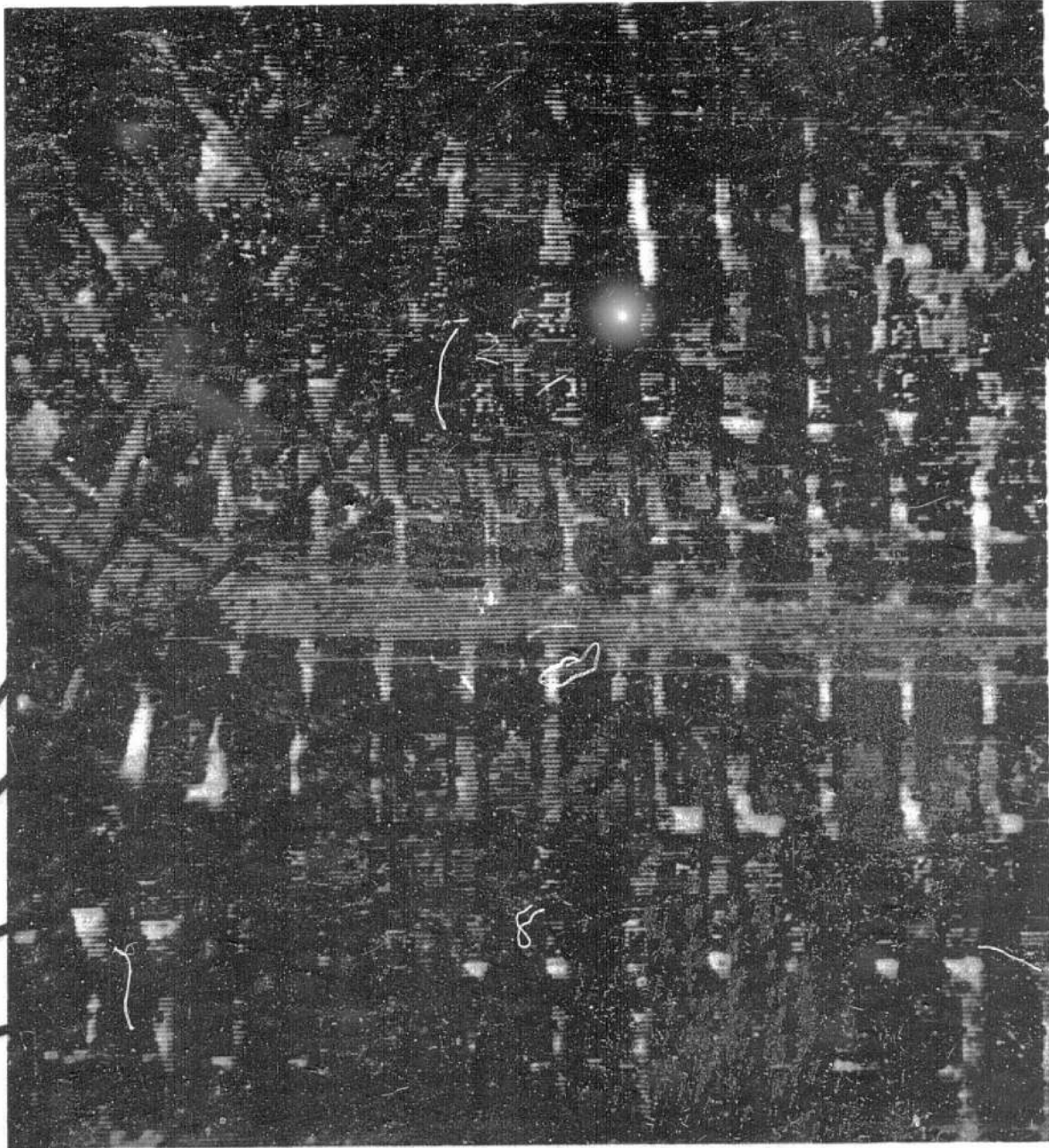
(a) Black-and-white thermograph with 12 temperature-calibrated densities.

Figure 6. - Typical thermographs.

NASA Color Thermographs show how much heat homeowners are losing



- Parked cars
- Garages
- Homes with high heat loss
- Homes with very high heat loss



Thermal infra-red data of HUD target areas obtained over Cleveland, Ohio on evening of March 24, 1977 10 P. M. weather clear, calm, w/air temperature 25°F.

National Aeronautics and Space Administration

(b) Color thermograph with 24 temperature-calibrated and color-coded densities.

Figure 6. - Concluded.

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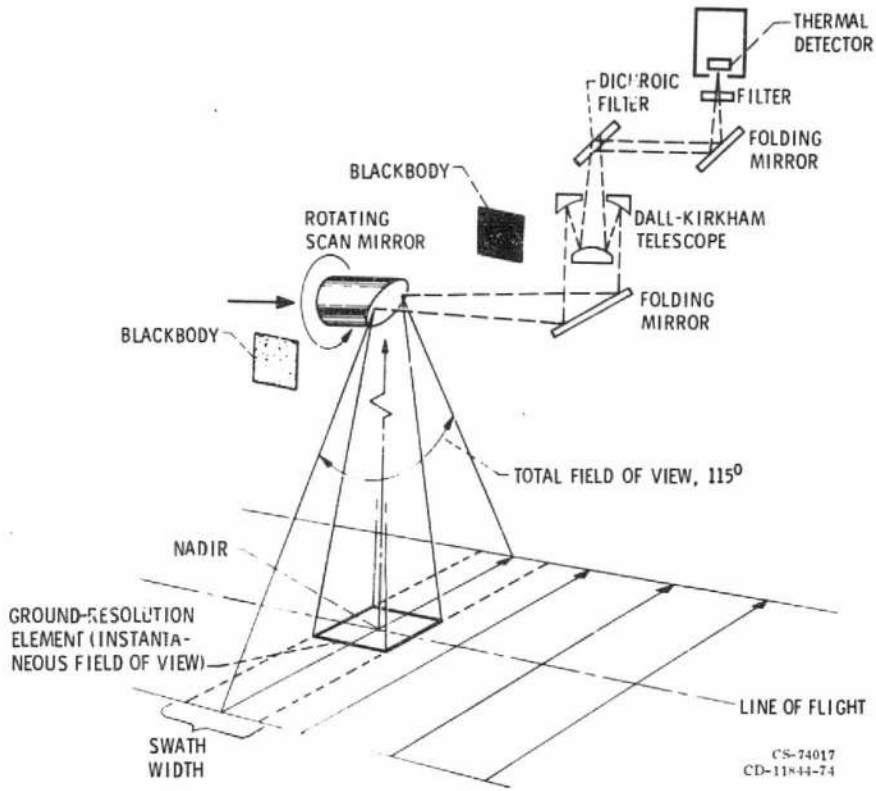


Figure 7. - Schematic of modular multiband scanner (M²S) system.

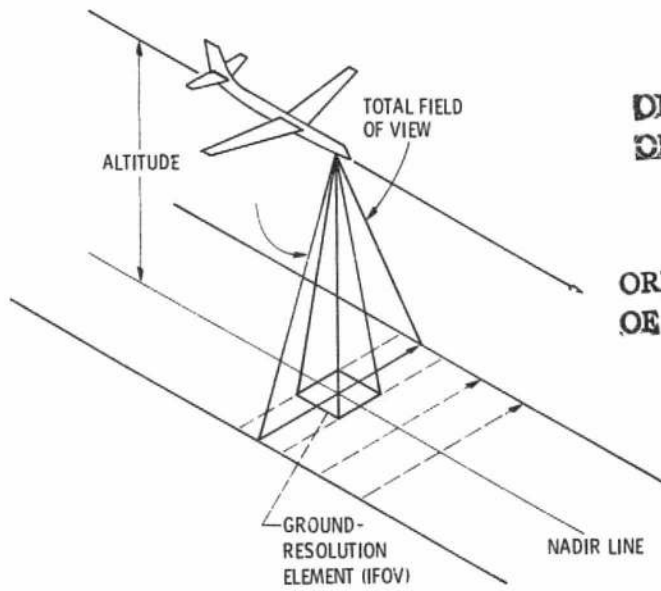


Figure 8. - Terrain scanning geometry.

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