

RESUME

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CLIMATOLOGY OF URBAN-REGIONAL SYSTEMS

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Urbanized areas have come to be significant if not dominant components of many regional land surfaces. They represent perhaps the most dramatic recent change man has made in his environment--a change that may well burgeon in the foreseeable future as greater percentages of world populations crowd into metropolitan areas. The climate of urban-regional systems is involved because temperature, air, and pollutants added to the air are significant aspects of this change. During the past two years, substantial progress has been made in the application of remote sensing techniques to the study of urban climatology by programs jointly sponsored by NASA and the United States Geological Survey. The initial effort has endeavored with considerable success to map terrestrial radiation emission or the general thermal state of the land surface with the aid of imaging radiometers (mechanical-optical scanners).

As its name implies, urban-regional climatology is dual in nature. One line of inquiry delves into the climate of the city itself. How do the various objects man has made create for him a different and perhaps detrimental environment? How do his activities create climates distinctly urban? The other line of inquiry is concerned with the way cities modify the climates of larger regions of which they are parts. Are temperatures developed over urban areas carried by winds out over adjacent rural lands? And what is the effect of a blanket of polluted air on the larger area?

It is useful to analyze urban climates in terms of energy systems. This helps in understanding the role of the large quantities of heat man adds to the city which must be dissipated in addition to the energy received from the sun. It gives quantitative insight into the disposal of solar energy by distinctive urban surfaces. Through the use of energy, the way pollutants hold back solar energy can also be studied

quantitatively. Absorption of solar energy and the radiation of energy from the terrestrial surfaces are parts of energy budgets which can be measured by the energy exchanges that are taking place. Most commonly measured are radiant fluxes, the shortwave energy from the sun and the interchange of longwave radiant energy between the surface and overlying air. A measurement from which useful inferences can be made is the balance of incoming to outgoing radiant energy flows, or "net radiation." A long-term net radiation deficit, for example, indicates that energy is being transferred from surface to air by non-radiant means such as transpiring plants. A long-term surplus might well indicate the transport of non-radiant energy into an area of concern such as a city. A change in this balance toward a consistent surplus is fundamental to the existence of cities as "heat islands" in their respective regions. Oppressive heat may be worsened when the energy absorption by living plants is diminished and a great deal of non-solar heat is liberated which sooner or later must be emitted from the urban surface.

The mating of remote sensing techniques to urban-regional energy climatology is desirable because of certain characteristics of the urban surface.

(1) It is highly three dimensional. Streets between rows of buildings become "thermal canyons" with many of the characteristics of the blackbody cavity of Kirchhoff. Radiant energy, absorbed and re-emitted repeatedly between building walls, results in almost total absorption of solar and atmospheric inputs despite albedos and emissivities of surface. An observer at street level, using traditional radiation measuring instruments, is within the cavity structure and, although he may be able to sense well the environment around him, he cannot assess the energy contribution to the open air over the city as well as can measurements made from above.

(2) The urban surface is a mosaic of smaller surfaces, each with its own radiant and thermal properties. A ground observer must attempt to extrapolate his point observations into a spatially complex system by assigning proportionality to the many types of surfaces he measures. This is an almost impossible endeavor without an airborne perspective (Figure 1). The new generation of mechanical-optical imaging radiometers capable of self-calibration automatically demarcates and measures characteristics of the many small surfaces that make up the urban mosaic. In Figure 1 both the urban mosaic and the urban-rural interface of Houston show well, imaged solely by the energy they are emitting in the thermal spectral band.

(3) Urban patterns of radiant exchange are constantly changing during diurnal and annual cycles. Relative radiant states may reverse between day and night. Blacktop is a good reservoir for solar energy, for example, and may not become as hot during the day as poorly conducting dry soil. This is apparent when one compares the cleared areas in the non-urban lands with the apparent radiation temperatures of the freeway and city streets in Figure 1. Had we a view of the same area made late at night, the pavement would be the warmer of the two. Thus there is reason to believe that synoptic maps of radiant exchange and thermal states may be of greater value in the analysis and monitoring of urban energy phenomena than maps laboriously compiled from statistical averages of difficult-to-obtain data collected at street level.

The application of remote sensing techniques to radiation climatology here described was carried out in conjunction with the Barbados Oceanographic and Meteorological Experiment (BOMEX) on the island of Barbados in the summer of 1969. The test site was a portion of the city of Bridgetown and adjacent agricultural lands. The imaging radiometer used was the RS-14 manufactured by the Texas Instruments Company. This instrument was one of the first of a new generation of "scanners" capable of quantitative calibration. A type of direct current electronic circuitry permitted operation along flightline without a change in the gain of the amplifier. In older types, frequent automatic change in gain prevented consistent calibration because a relation between surface radiation and instrument output established for one part of the image would not apply to other parts. Calibration is aided by initial recording of the full range of detected energy modulations onto magnetic tape. When these energy signals are converted to a photographic image in the laboratory, further adjustments can be made to maintain the full range of energy modulations as density differences on the film. A further aid that should become increasingly useful in the future are internal reference energy sources within the instruments which record with the image and aid in quantitative calibration. Although the initial experimental work relied primarily upon ground calibration targets, internal energy sources in the RS-14 although still without final calibration, permitted tentative equations to be formulated which in the future may reduce the dependence upon ground cross-calibration.

It should be understood that an imaging radiometer does not make a photograph of the surface it images. Rather, it records the energy being emitted by the surface, not reflected sun energy. Thus if it can be calibrated it becomes a true radiometer with the

added capability that energy it records can be converted to an aerial-type image from which a map of energy emission can be made. Further, since the energy emission is related to the temperature of the land surface, a fairly good picture of surface temperatures is obtained. Since the earth is much cooler than the sun, it emits energy in wavelengths much longer than light. In reality, the earth surface is imaging itself with its own energy emission. Quantitative calibration of the image is useful in the study of the climatic relationships of the surface being imaged.

The flightline chosen for the mapping experiment extended inland from the west coast of the island of Barbados across the northern suburbs of Bridgetown to sugar cane fields inland and presented a good contrast of rural and urban lands. Cloud shadows from a daily cumulus buildup presented a problem, since these comprised short-lived areas of cool surface that persisted for some moments after the shadow had moved on.

Initial cross-calibration between the surface and the airborne sensor was empirical. Ground calibration surfaces or "targets" had been selected, the radiation temperatures of which were measured during the overflight. The adjacent sea surface, of known temperature, was also used for calibration. Surfaces chosen as targets were large enough that the optical transmittance of them on image transparencies could be subsequently measured during data reduction. Target radiances were measured with an absolute calibration instrument, the Barnes Engineering Company PRT-5 Precision Radiation Thermometer.

The initial data reduction problem was to relate transmittances of the radiometric image to surface radiances at the time of overflight. This was accomplished with the aid of a transmission densitometer by measuring the transmittances of the images of ground targets. Since the image was positive, transmittance was used rather than density to avoid an inverse relationship. Sea-surface radiance was used to anchor one end of an appropriate conversion curve and land calibration targets the other in order to make the graphical plot shown as curve A of Figure 2.

To make isoline maps that would show meaningful patterns of terrestrial radiation, it was necessary to generalize the minute patterns of the radiometric image, particularly over the urban area. To accomplish this, the image was divided into a matrix of choropleth cells one centimeter square or close to one-half kilometer square on the ground. A silicon cell device with an area equal to a matrix cell was first calibrated to the densitometer (curve B, Figure 2) and was then used to integrate each cell

transmittance. The matrix, superimposed upon the scan image, is shown in Figure 3a, and derived averaged transmittances in Figure 3b. With the aid of a computer, slope equations for curve B then converted the averaged cell transmittances to the radiances shown in Figure 3c. Mapping (Figure 3d) involved the use of the centers of the averaged cells as control points from which to plot the desired isolines. Maps in other radiation terms were made in the same manner and appropriately all showed the same radiation patterns.

As previously noted, the RS-14 has built-in calibration sources which give the instrument a self-calibration potential. The radiances received aloft by the instrument, however, are not the same as the radiances emitted by the surface being imaged. Intervening air, even in the 8-14 micron wavelength water vapor window, both attenuates the surface signal and adds an energy component of its own. Realization of the full potential of an imaging radiometer, then, necessitates that the error induced by the atmosphere be systematized in order that a correction without elaborate ground controls be carried out. For the Barbados data, this has been accomplished by using a gray-window model for the intervening air expressed by the equation:

$$I_z = \epsilon [E_{bb}(\bar{T})] + (1-\epsilon) I_o$$

where (I_z) is the radiance at the sensor, (I_o) the radiance of the surface target, [$E_{bb}(\bar{T})$] the blackbody equivalent of the mean temperature of the intervening air column, and epsilon the effective emissivity of the air column in the spectral band being sensed. When values for sensor and surface radiance (I_z and I_o) are known from instrument readout and ground calibration and a mean air temperature has been established, the effective emissivity of the air, or epsilon (ϵ) in the equation, can be determined. This value permits the mathematical computation of surface radiances (I_o) for all values of sensor radiance (I_z) which in turn permits plotting a correction curve (Figure 4) that will fit all parts of the scan image if the intervening air is considered to be relatively homogeneous.

Although at the time of the Barbados flight, the internal calibration sources of the RS-14 were not deemed to be working properly, Victor Whitehead of the NASA Earth Observation Program systematized the error well enough to obtain image vs radiation temperature values which, when corrected for the effects of the atmosphere by the foregoing equation, corresponded closely to values derived from ground calibration targets.

Certain characteristics of the relationships just described may in the future significantly reduce the amount of ground calibration necessary. The slope of the correction curve is equal to the reciprocal of the air transmissivity ($1/1-\epsilon$) and can thus be set by a single ground calibration which permits determination of the effective air emissivity in the spectral band being utilized. The position of the curve with respect to the I_z axis of the graph is established by the fact that the curve must intersect a line of equal value at a radiance equal to the blackbody equivalent of the mean temperature (\bar{T}) of the intervening air column. Further, according to Beer's Law, the transmissivity of the air is also equal to the natural log base (e) to the minus (ku) power where (k) is the absorption coefficient of the spectral band of concern and (u) the optical depth of the intervening air in gram-centimeters squared of precipitable water. Thus the slope of the correction curve is also equal to

$$1/e^{-ku}$$

a relationship which should permit setting the slope without the aid of ground controls, solely from atmospheric data, when more knowledge has been collected regarding absorption within the water vapor window. Elimination of ground controls may be particularly important when the system is applied to earth-viewing satellites with a thermal sensing capability, such as ERTS-B.

The foregoing radiation mapping project must be considered a pioneer effort. The optical integration method has certain inherent potential errors relating to the linearity of translating energy received by the airborne sensor to film densities. Computer programs are now being adapted to yield the matrix cell generalization directly from the magnetic tapes to reduce this possible source of error. It is recognized that sides of a scan are not viewed vertically which may produce errors since three-dimensional surfaces in all probability do not emit equally in all directions. Planimetry of the maps must be adjusted for changes in airplane course and attitude. The maps are successful enough, however, to indicate that rapid production of synoptic radiant emission maps with imaging radiometer data is sufficiently feasible to warrant further study toward refinement and adaptation as an operational system.

Future progress in achieving an ability to remotely monitor urban-regional energy budgets must follow two paths. First, the sensing capability must be extended to include fluxes other than terrestrial longwave emission. Investigation this past summer

indicates that surface albedos can be determined photographically or perhaps better by the use of other channels of the imaging radiometer that will sense solar radiation. With ground pyranometers to check solar input, the addition of albedo measurements may make possible the construction of synoptic maps of net radiation, adding this valuable analytical tool to radiation analysis.

The second path toward improvement involves the application of the methods developed from data acquired in the single flight over tropical Barbados to a sequence of flights over a midlatitude city in the United States. Derived maps can show patterns of both diurnal and annual change for a variety of phenomena related to radiant exchange. First will be an initial sequence of four flights with appropriate sensors to sample a diurnal period. This sequence logically should be followed by similar diurnal sequences at other seasons to demonstrate annual change in patterns.

The continuing effort is a logical preliminary toward giving the earth resource satellites the capability to monitor urban-regional climatic elements. A "pre-calibrated" city will help in calibrating ERTS instruments. Previously acquired knowledge pertaining to the target city will be augmented by aircraft and ground data observed at the time or times of satellite passage. Present planning calls for establishment of several automatic platforms around the city which will transmit at least daily records of selected surface radiation information to ERTS for subsequent retrieval.

If we are successful in quantifying ERTS outputs for the target city, attempts will then be made to apply the methods to other urban-regional complexes without resorting to ground truth.

The question naturally arises as to the practical use of the methods of study described. Rapidly made radiation maps should help in understanding the causes of problems in urban environments that relate to climate. With a better understanding of the problems either remedial action can be taken to alleviate them or they can be lessened by wise future urban planning. The three-dimensional nature of a city, for example, creates what Lettau and others have termed a "roughness factor." This roughness can interfere with ventilating winds creating problems of excess temperature and stagnation of air. Proper spacing of high-rise buildings can reduce interference with city ventilation, improve the temperature environment, and reduce the collection of atmospheric pollutants. Measurement of conditions of net radiation may indicate the desirability of providing "greenbelts" and

open spaces within an urban area and give suggestions as to the most effective locations for them in a particular city situation. Study of the thermal cavity structure of a city may suggest that a variety of building heights along a given street is preferable to the common thermal canyon structure. On the other hand, winter maps may show that changes beneficial to summer climates make winter cold more severe. Only with a considerable body of knowledge derived from the operation of such a mapping program can problems of these types be best solved.

Since cities are dynamic and growing, change is an important factor to study. In a sense we have simply drifted into our present urban-regional climates. Rapidly made synoptic radiation maps, perhaps derived from satellite observations, will enable governments to monitor the changes that are taking place and replace aimless drift with wisely planned change.

As Outcalt has broadly stated, "... a reasonable programme goal is the prediction of the effects of land-use manipulation on the climates of urban areas." To this we add, "... and on the regional climates which urban areas help to create." At this point, a path toward an operational capability beings to take shape. By the endeavors of this program of investigation it is hoped we can gain the ability to monitor rapidly urban-induced changes in the climatic aspects of man's environment.

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DEFINITION OF TERMS

(In order of appearance in text)

Energy exchange system: Local climates as well as world wide are to a great extent conditioned by the exchange of energy between the surface and overlying air. The overall system includes the transfer of energy by radiant exchange, by conduction, and in a non-sensible form through evaporation and the transpiration of plants.

Longwave radiation: The peak wavelength of a radiant energy package depends upon the temperature of the source. Since the sun is very hot, the energy it emits is shortwave. Energy emitted by the much cooler earth is considered longwave.

Radiant flux: The flow of radiant energy in a given direction. Most commonly we speak of downwelling and upwelling fluxes.

Energy sink: Objects or processes by which energy is absorbed or removed from a radiant exchange system.

Blackbody cavity: See emissivity.

Albedo: The fraction of solar or shortwave radiation reflected by a surface. The fraction reflected is usually expressed as a percent.

Emissivity: The effectiveness of a surface in emitting radiant energy for a given temperature as compared to the radiation of a perfect blackbody. It is equal to the effectiveness of absorption of the surface or absorptance. A perfect blackbody, according to the concepts of Kirchhoff, absorb all radiant energy striking it. A blackbody cavity increases the efficiency of

absorption by emitting and reabsorbing energy within it until virtually all energy entering the cavity has been absorbed, regardless of actual emissivities of the cavity surfaces.

Imaging radiometer: A device, capable of calibration, for imaging radiant energy too long in wavelength to affect photographic film. It consists of mirror systems and a detector capable of reacting to the desired wavelengths. Although the imaging is done electronically, a final display may be made on photographic film. Also termed mechanical-optical scanner and electro-optical scanner, although the term "radiometer" should not be applied to older type instruments.

Thermal spectral band: Radiant energy varies according to wavelength. Visible light has wavelengths that range from .4 to .7 microns. One micron is 1/1000 of a millimeter. The near infrared extends from .7 microns to 3 microns. Thermal infrared or the thermal spectral band extends from 3 to 100 microns. It gains its name from the fact that the general range of temperatures found at the surface of the earth emit radiant energy mostly with these wavelengths. See also longwave radiation.

Blacktop: The common name given to asphaltic concrete used for pavement. Also known as "tarmac" and "Macadam."

Synoptic maps: Maps made to portray conditions as of a given instant.

Radiance: A quantitative measurement of the intensity of radiation emitted by a surface. It is defined as watts per square centimeter per solid angle or steradian.

Optical transmittance: The fraction of the light falling upon a substance that passes through it, in this case an area of a photographic transparency.

Density: The measure of the opaqueness of a photographic transparency. It is the logarithm of the reciprocal of the optical transmittance.

Densitometer: An instrument for measuring the transmittance and density of a transparency.

Isoline: A line connecting points of equal value. Examples are isotherms and isobars on a weather map. Lines mentioned here connect points of equal radiance.

Chloropleth: A statistical area treated as a whole. For purposes of convenience, all parts of the area are considered to have the same value or an average value.

Air transmissivity: The measure of the fraction of radiant energy that will pass through a given mass of air. That not transmitted is either absorbed or scattered.

Water vapor window: In the thermal infrared spectral band, water vapor is an efficient absorber of radiant energy, effectively reducing the transmissivity of the air. Between 8 and 12 microns, on the other hand, water vapor is a poor absorber and radiant energy with these wavelengths penetrates air best. This spectral band is commonly called the "water vapor window," although other smaller windows occur.



Figure 1 -- The interface between rural and urban surfaces at the edge of Houston, Texas as imaged by the RS-14 scanning thermal radiometer. Light tones represent relatively high emission of radiant energy or "radiance." Dark tones are lower levels of emission. From this image it can be clearly seen that an urban surface is a mosaic of sub-surfaces, each with its own thermal and radiant properties.

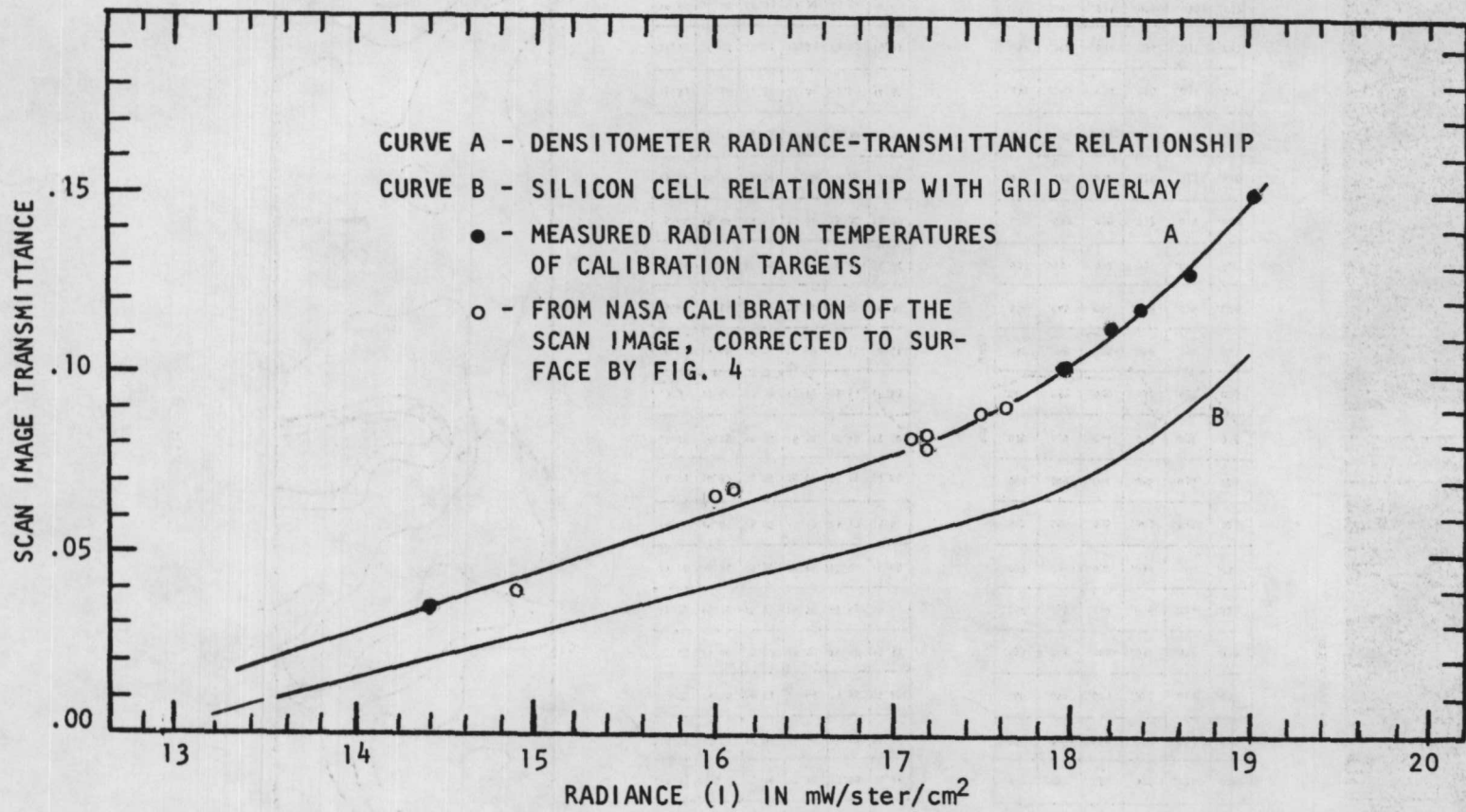


FIG. 2. RADIANCE - TRANSMITTANCE RELATIONSHIPS



SUGAR CANE FIELDS

BRIDGETOWN

a.

RURAL URBAN

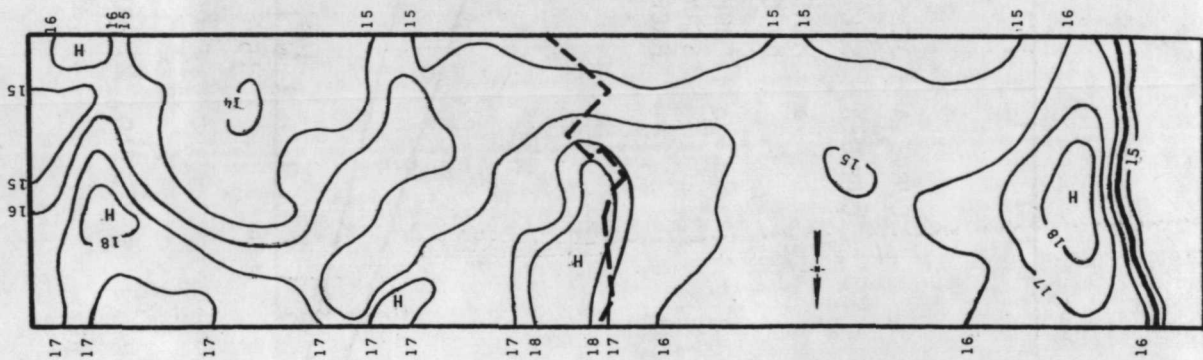
RURAL		URBAN	
.050	.048	.040	.020
.054	.062	.070	.045
.043	.057	.056	.030
.054	.058	.082	.020
.064	.040	.023	.022
.055	.042	.029	.031
.038	.038	.054	.038
.057	.034	.032	.045
.042	.050	.036	.043
.043	.049	.042	.036
.070	.070	.046	.048
.067	.083	.080	.058
.042	.049	.053	.048
.034	.046	.044	.048
.033	.035	.038	.035
.029	.039	.039	.037
.032	.038	.032	.028
.032	.038	.030	.036
.039	.040	.050	.028
.047	.042	.051	.035
.050	.060	.071	.064
.056	.078	.082	.075
.049	.032	.025	.043
.021	.019	.020	.021

b.

RURAL URBAN

RURAL		URBAN	
16.65	16.50	15.90	14.70
16.95	17.55	18.15	16.28
16.13	17.18	17.10	15.15
16.95	17.25	15.07	14.40
17.70	15.90	14.63	14.55
17.03	16.05	15.08	15.23
15.75	15.75	16.35	15.75
17.18	15.45	15.30	16.28
16.05	16.65	15.60	16.13
16.13	16.57	16.05	15.60
18.15	18.15	16.35	16.50
17.93	18.44	18.34	17.25
16.05	16.58	16.88	16.50
15.45	16.35	16.20	16.50
15.38	15.53	15.75	15.53
15.08	15.82	15.83	15.68
15.30	15.75	15.30	14.96
15.30	15.75	15.15	15.60
15.83	15.90	16.65	15.00
16.42	16.05	16.73	15.53
16.65	17.40	18.03	17.70
17.10	18.27	18.41	18.17
16.58	15.30	15.08	16.13
14.48	14.33	14.44	14.44

c.



d.

Fig. 3.

Figure 3 -- The sequence of operations to transform a thermal scan image into a generalized map of radiance, utilizing optical means. The maps are for Bridgetown, Barbados, made June 27, 1969 by NASA Mission 98, 10:30 AM local time.

(a) The calibrated image from the RS-14 scanning radiometer. Included in the image are two control targets for which radiation temperatures at the time of overflight are known. Average transmittances for each cell of the choroplethic grid are optically determined with a silicon integrating device.

(b) The matrix of choropleth cells with average optical transmittance indicated for each.

(c) The matrix of choropleth cells with transmittances converted to average radiances according to a transmittance-radiance relationship determined both by the ground control targets and by mathematical equations. Computerized methods were used to facilitate the many transformations required. Radiant emission could also have been expressed as radiation temperature or as radiant flux in either milliwatts per square centimeter or langleys per minute.

(d) An isoline map of generalized radiance for Bridgetown and adjacent rural lands, drawn by using the centroids of the choropleth cells as control points. This map gives a picture of both the thermal state of the mapped area at the moments of overflight as well as the contribution of energy emitted by the surface to the overlying air.

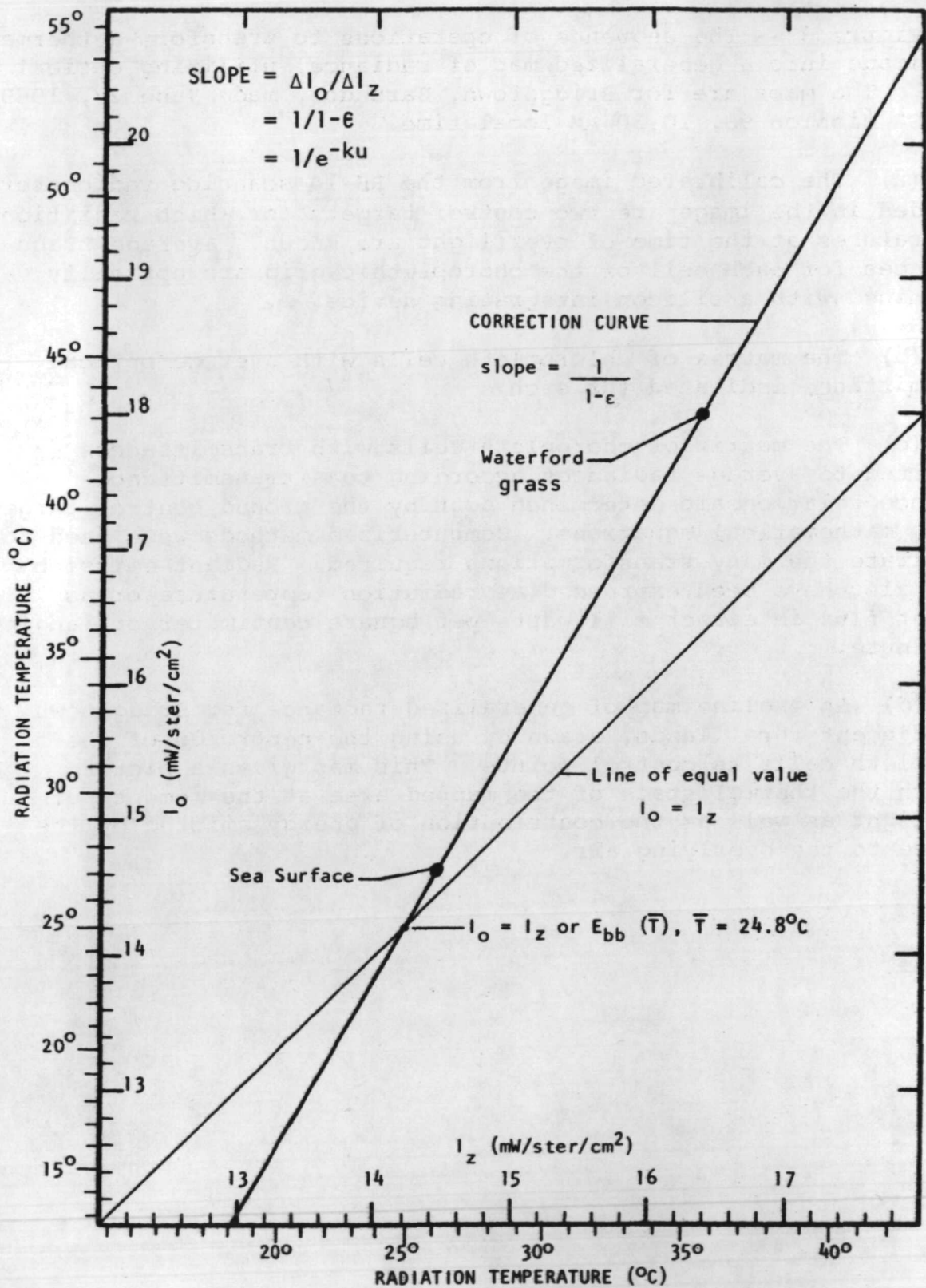


FIG. 4. SURFACE-TO-SENSOR RADIANCE ADJUSTMENT