THE NATURE OF INFRARED RADIATION AND WAYS TO PHOTOGRAPH IT

by

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Definition

Infrared radiation is electromagnetic radiation having wavelengths between .7 and 1000 microns. A micron is one millionth of a meter, and to persons familiar with angstrom unit measure, the wavelength range is between 7000 angstroms and 10 million angstroms. The chart (fig. 1) taken from Aviation Week shows the relation of infrared wavelengths to the wavelengths of other radiation.

Generation of Infrared

All material things radiate infrared radiation as long as they are above absolute zero temperature. For example, $1m^2$ of black surface at room temperature radiates 460 watts. This radiation arises from the thermal agitation of the charged particles of which all material is composed. The ability of a body to radiate infrared is determined by two things -- the temperature of the body, and its surface condition which is measured by the emissivity. As the temperature of a body increases, the vibration amplitudes and frequencies of the atoms and molecules composing the body also increase so that the radiation of infrared from a heated body increases with the temperature; in particular, the total radiation is roughly proportional to the fourth power of the absolute temperature. The emissivity is simply a measure of the special characteristics of the surface material of the body.

Materials such as gases radiate in bands or line spectra characteristic of the properties of the individual molecule because of the relative isolation of the various molecules composing the body of gas. However, due to the close association of molecules or atoms in solids, the interference of characteristic vibrations of molecules tends to produce a common type of spectrum. This spectrum is similar to the theoretically ideal emitter called the blackbody. Actually, no such blackbody radiator exists in practice although experimentally very good approximations for this type of radiation can be obtained.

In fig. 2 from Aviation Week, March 1957, is shown the spectral distribution of an ideal radiator at various absolute temperatures. Vertically, on the graph is the spectral radiant intensity of a blackbody source. This is plotted horizontally against wavelength in microns. Notice that this characteristic radiation increases enormously with temperature as is measured by the area under the curves. Notice also that the wavelength for the maximum radiation moves over toward shorter wavelengths with increasing temperatures. These curves show the maximum power which a material body can emit at a given temperature and at any particular wavelength. All real bodies emit spectra which are modifications of these but in no case can the radiation of a body at a fixed temperature rise above that shown by the corresponding blackbody curve.

A law known as Kirkoff's law requires that a body which emits well at a given wavelength must also absorb well at that same wavelength. For example, a silvered surface will emit poorly even at high temperatures. The spectral distribution will peak in the short wavelength range, nevertheless, which is proper for the high temperature. Some objects emit well at some wavelengths and emit poorly at others. This is particularly the case with gases. Clearly, any body which is transparent at a given wavelength cannot absorb at this wavelength by definition. Therefore, it also cannot emit well at that wavelength.

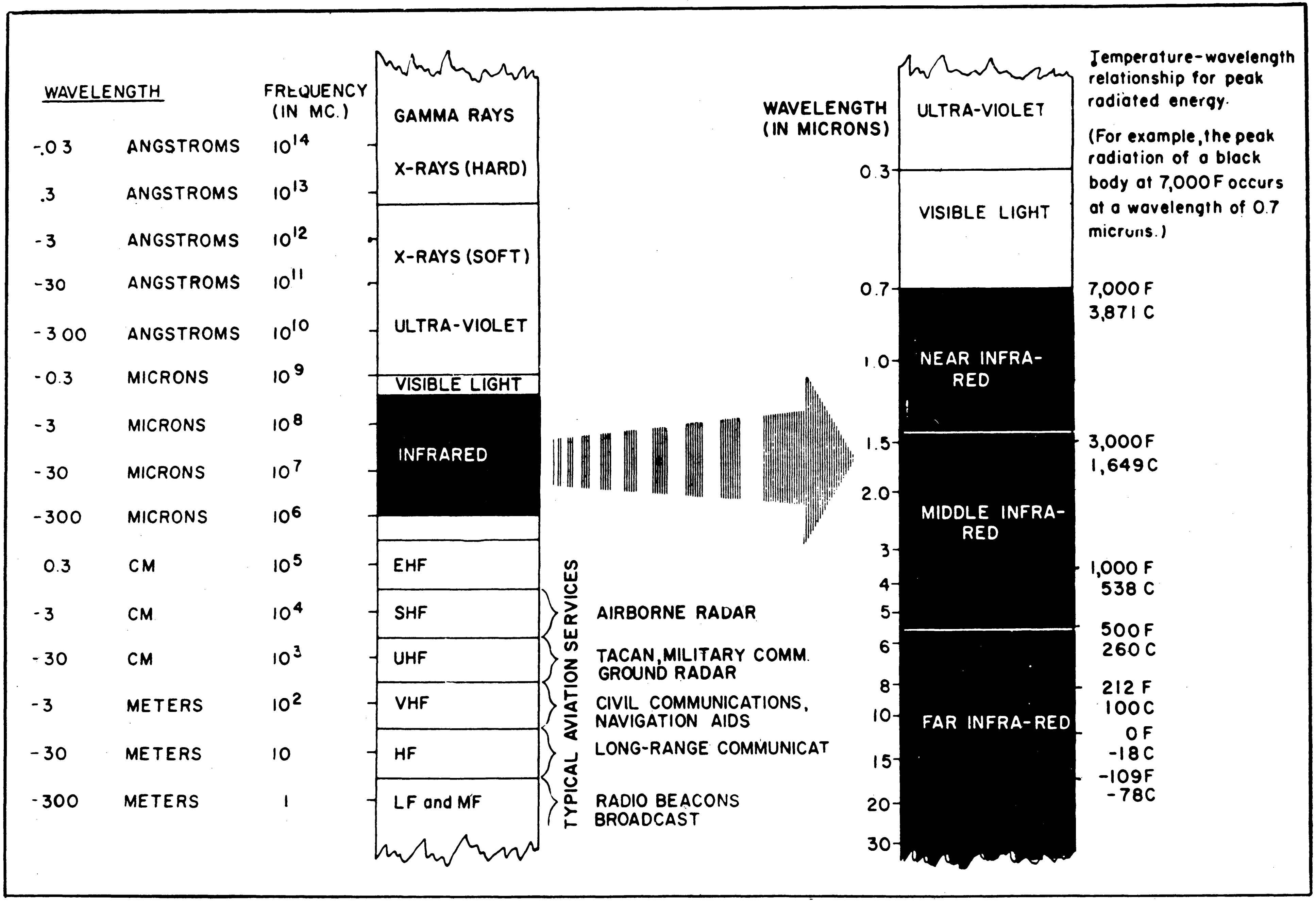


Fig. 1 Relationship of Infrared Wavelengths to Wavelengths of Other Radiations. (Aviation Week, March 1957)

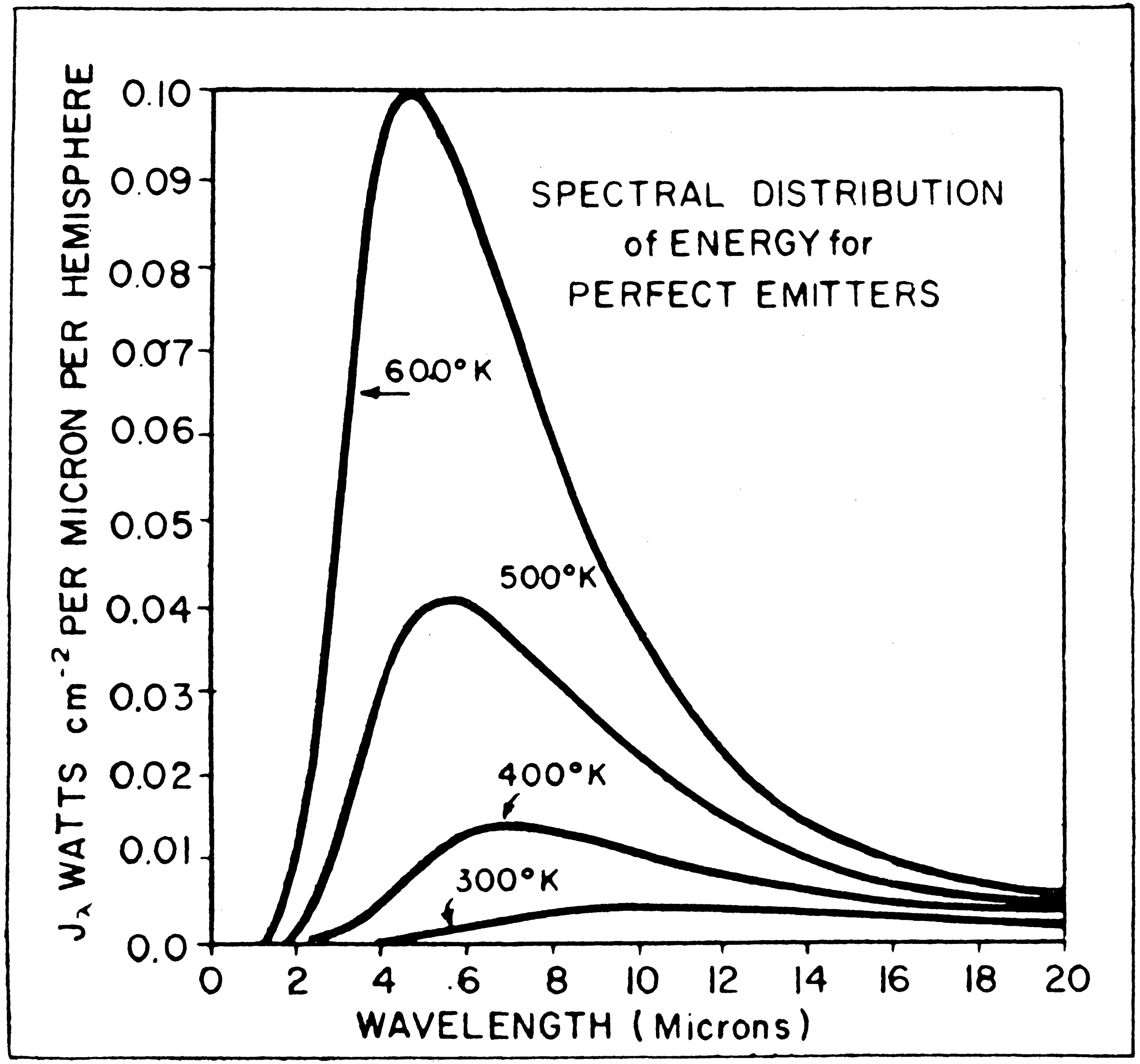


Fig. 2 Spectral Distribution of Power Radiated from Black Body Sources. (Aviation Week, March 1957) The temperature of a warm room is about 300°K. Soldering iron temperature is between 500°K and 600°K. These curves should approach the base line asymptotically on both short and long wavelength sides.

Near Infrared Photography

If one wishes to photograph the earth's surface, it is apparent from the figure that the amount of radiated power coming from the earth's surface is quite insignificant in the visible and near infrared regions of the spectrum. For this reason, the reflected radiation from a much higher temperature source must be employed to successfully expose photographic film or actuate a T. V. camera tube because these are not sensitive to radiation having longer wavelengths than about 1 u. The wavelengths of radiation between .7 u and about 1.5 u (the near infrared) are not difficult to record by standard means. In that respect, the recording of near infrared is not significantly different from the recording of visible radiation. However, the recording of 1.5 u and longer radiation is not yet feasible with simple extensions of current standard practices using photographic cameras and photo-emissive T. V. camera tubes.

For the photograph of near infrared radiation, the best single reference is the book by Walter Clark, Photography by Infrared, 2nd ed., Wiley and Sons Inc., New York, New York, 1946. I will not discuss the standard practices further, but would like to turn to the discussion of the techniques for the photography of the earth glow radiation.

Photography by Earth Glow Radiation

In order to photograph any object, the camera must be sensitive not just to the total radiation but also to the contrast in radiation between areas in the field of view. This contrast can be either in intensity or in spectral distribution or both. To photograph radiation having longer wavelengths than 1 1/2 u, we must detect contrast in radiation either reflected or emitted from the objects in the field of view and therefore must be able to detect differences either in spectral distribution or amounts of radiation coming from these objects. The fig. 3 taken from the Syracuse University final report "Infrared Spectral Emissivity of Terrain", April 1958, show the spectral distribution radiation longer than 1 1/2 u from snow on a clear day, a red brick wall and a concrete slab. The lower curve indicates the spectral distribution of radiation coming from grass on an overcast day. Notice that the spectral power as indicated from 1 1/2 to 3 u is the effect of solar radiation reflected from the surface of the object. This solar reflected power is decreasing with increasing wavelengths until the radiation emitted by the object is dominant. The cross-over point where the emitted radiation becomes dominant over the solar reflected radiation is approximately at 3 u.

If we are to photograph a composite scene containing a snow field, a red brick wall, and a concrete slab all at the same ambient temperature of 4^{o}C., we must detect the differences of the areas under each of the curves. It is easy to see that the differences are much smaller than the total power radiated by each object. Notice also the similarity of these curves. This indicates that the ability to emit or reflect radiation in the spectral region is not strongly dependent upon wavelengths for these common surfaces. While the complete curve extending to longer wavelengths in the infrared is not shown here, it is reasonable to expect that these curves all proceed toward a maximum at 9 or 10 u and then proceed down asymptotically to zero at infinite wavelengths. This graph showing the spectral distribution of real physical objects on the earth's surface is typical of the spectra which we must use in our recording devices.

The surface temperature of various objects on the surface of the earth will

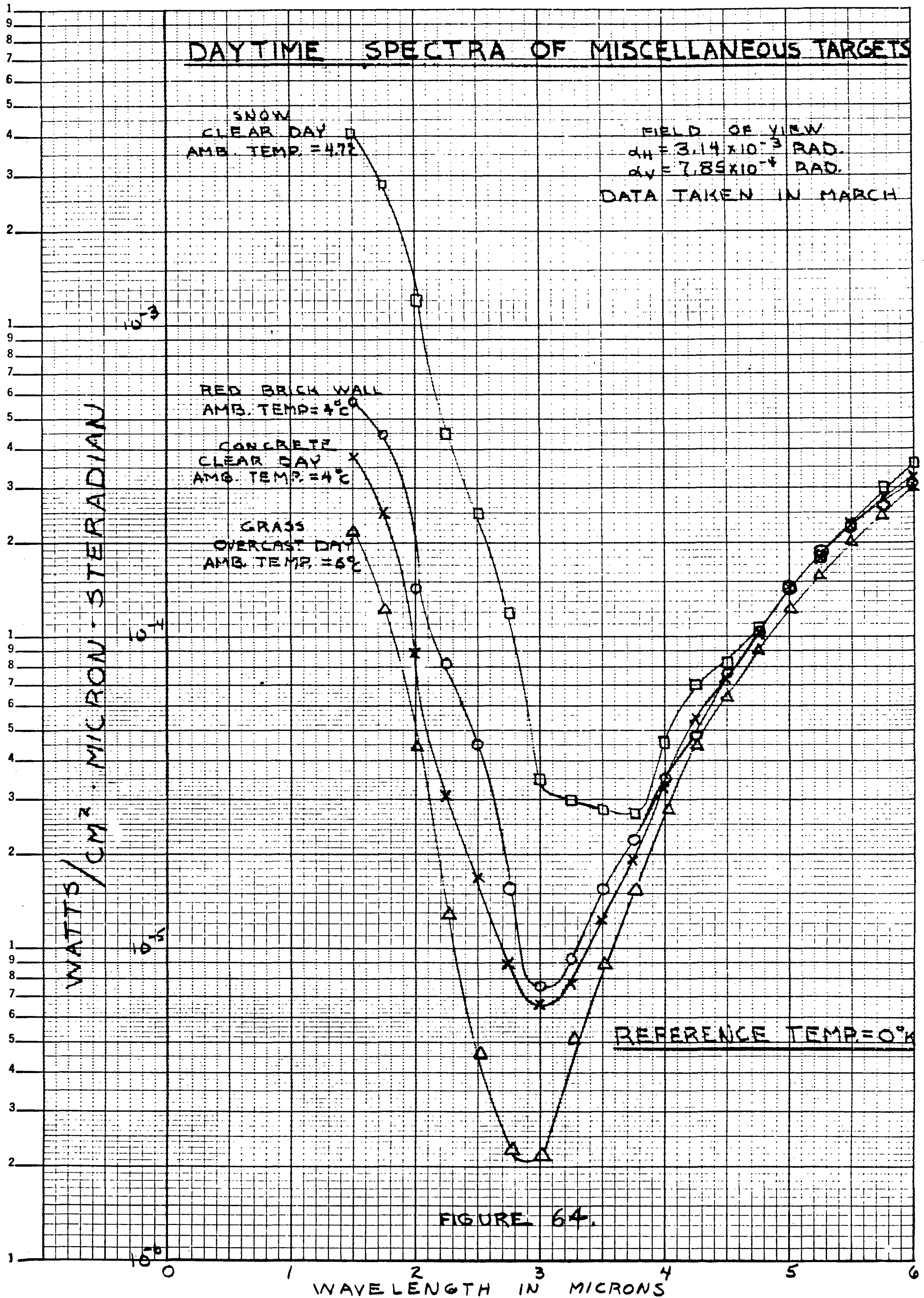
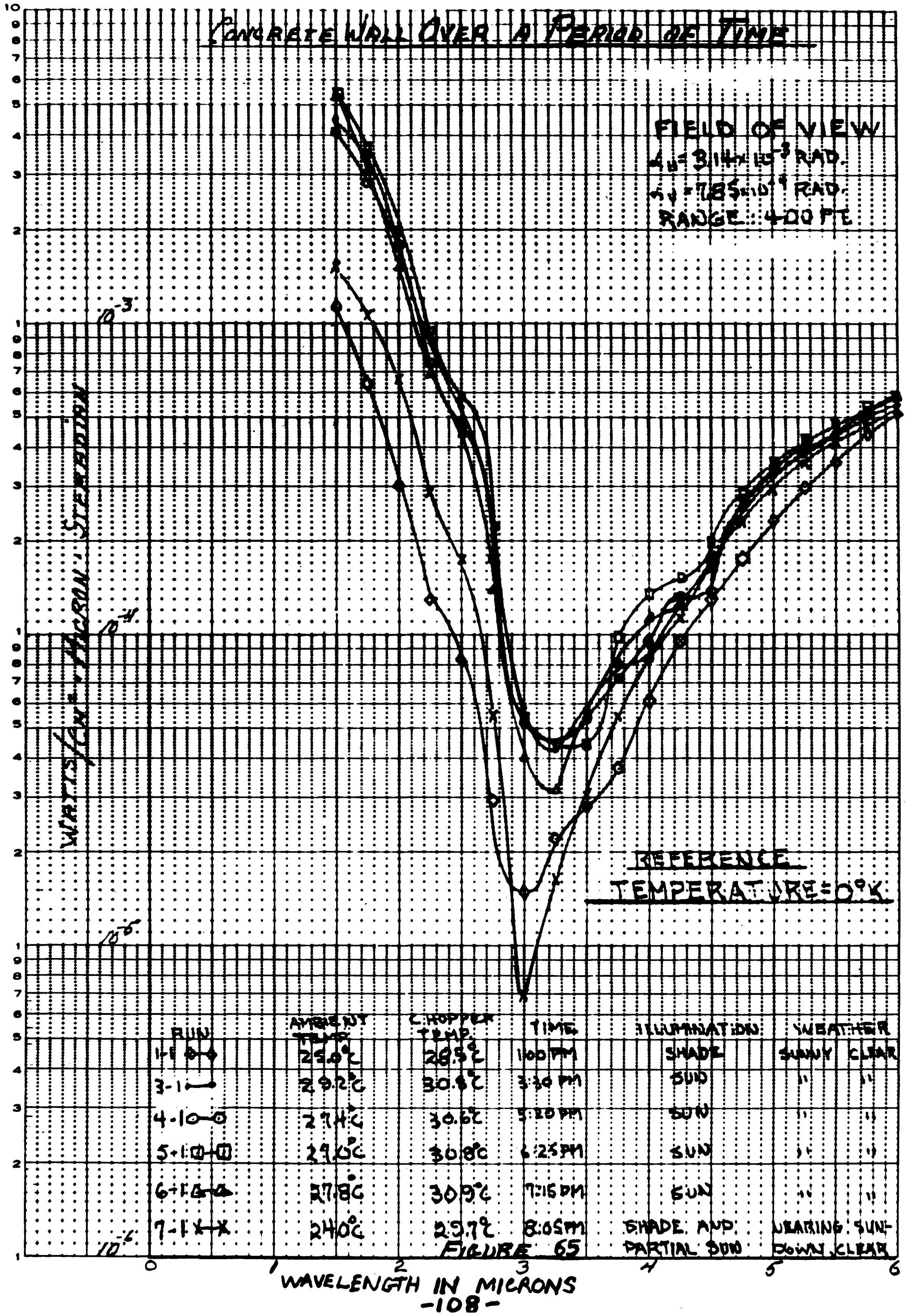


Fig. 3a Daytime Spectra of Miscellaneous Targets
This graph was taken from a Syracuse University Research Institute Report WADC-TR-58-229 (1958). It shows the typical infrared spectrum of daytime common surfaces. For wavelengths shorter than 3 microns to solar reflected radiation is the largest contribution. Earth glow contribution is dominant for wavelengths longer than 3 microns.



RUN	AMBIENT TEMP.	CHOPPER TEMP.	TIME	ILLUMINATION	WEATHER	
1-1 ◆-◆	25.0°C	28.5°C	1:00 PM	SHADE	SUNNY	CLEAR
3-1 •—•	29.2°C	30.8°C	3:30 PM	SUN	"	"
4-10 ○-○	27.4°C	30.6°C	5:20 PM	SUN	"	"
5-1 □-□	29.0°C	30.8°C	6:25 PM	SUN	"	"
6-1 △-△	27.8°C	30.9°C	7:15 PM	SUN	"	"
7-1 X-X	24.0°C	29.7°C	8:05 PM	SHADE AND PARTIAL SUN	NEARING SUN-DOWN,	CLEAR

Fig. 3b Daytime Radiation from Concrete Wall.
Notice that the expected variation in spectral radiance under various conditions from the same object is almost the same size as the variations of radiance of different objects under similar conditions as shown in Fig. 3a

be substantially different. One may confirm this from his memory when he was younger during his barefoot days. Without doubt, there is no one here who has not at one time walked about during the summer with bare feet and felt the coolness of the grass and the lukewarm feel of packed earth and the intense and almost painful heat of the hot sidewalk to the bare feet. These temperature differences will be reflected in the amount and spectral distribution of the infrared radiation being emitted. In turn, the temperature differences which arise will be governed by the ability to absorb solar radiation. These two capabilities are not necessarily the same. The greenhouse effect is a notable example.

At night time, the residual heat left in the field objects from the solar heating is emitted back out into space. As the night draws on the temperatures gradually fall or may remain steady depending upon air temperatures, air velocities, overcast conditions or whatnot. These continually varying surface temperatures provide us with the contrast which we are to see in our photographic recording of the radiation in these wavelength regions.

Atmospheric Absorption

In general, we will expect to photograph the earth's surface through a certain amount of atmospheric gases. We must, therefore, consider the transparency of the atmosphere for radiation of these wavelengths. Figure 4 taken from Aviation Week, March 1957, shows the atmospheric transmission. The infrared radiation which is spread over a broad spectral range is selectively absorbed by the atmosphere. The atmosphere, being a material body itself, also emits infrared radiation characteristic of its temperature and constituent gases. The overall effect of this atmospheric filter and radiator is to reduce and alter in other ways the contrasts that are inherent in the sources of radiation which we wish to view.

Recording Systems

The radiation which finally arrives at an infrared recording system is first brought to focus by optical surfaces to a detector. This is entirely parallel to the functioning of a camera operating in the visible region. The detector translates the fluctuations of infrared radiation into fluctuations in electrical currents. This detector is more properly called a transducer since it transforms signals from one form of energy to another. The detector is analogous in function to the photomultiplier cells which can be used to detect visible light intensities. After the signals have been transformed into a-c electrical currents, amplification of these signals can be done easily by suitable electronic means.

If one desired to make a full photographic coverage of a scene, one can use a single element having a very narrow field of view and scan this small element over the full field of view to be photographed. Figure 5 illustrates one of the many possible scanning methods which is capable of providing continuous ground coverage from an airborne equipment. The instantaneous field of view is scanned from one side to the other. The aircraft motion carries the equipment over to the next scan line position in time for the next scan to begin.

In the case of the visible photographic camera, every sensitive grain in the emulsion performs the function of the transducer and there are many of these grains. In the case of the infrared scanning system, there is, so to speak, only one grain which must be used in time sequence. This grain is usually made of a thin small

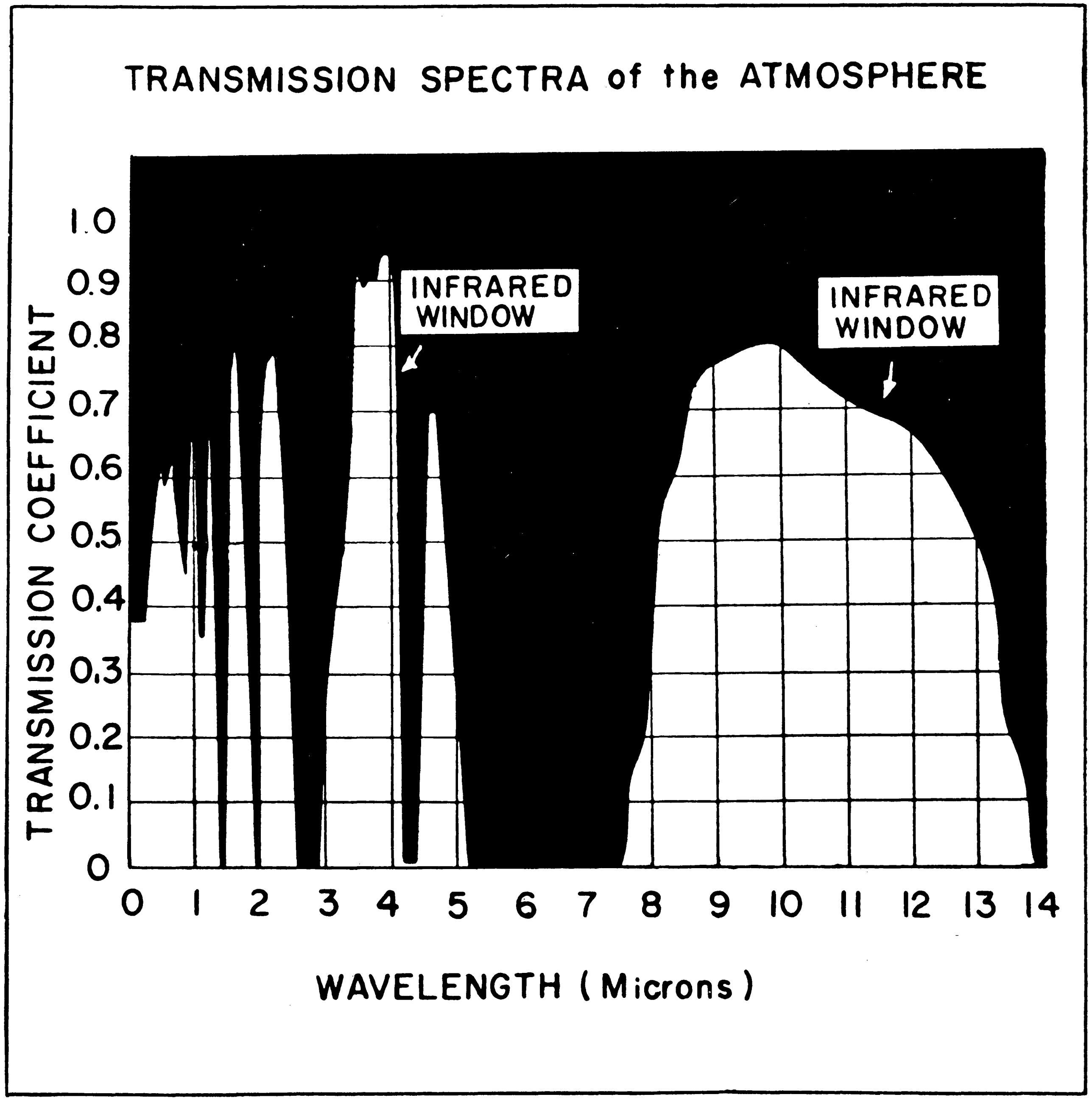


Fig. 4 Transmission Spectrum of the Atmosphere (Aviation Week, March 1957)
While the transmission varies from time to time, this graph shows the typical transparent spectral regions which are encountered.

Strip Mapping Scanner - Method of Scan

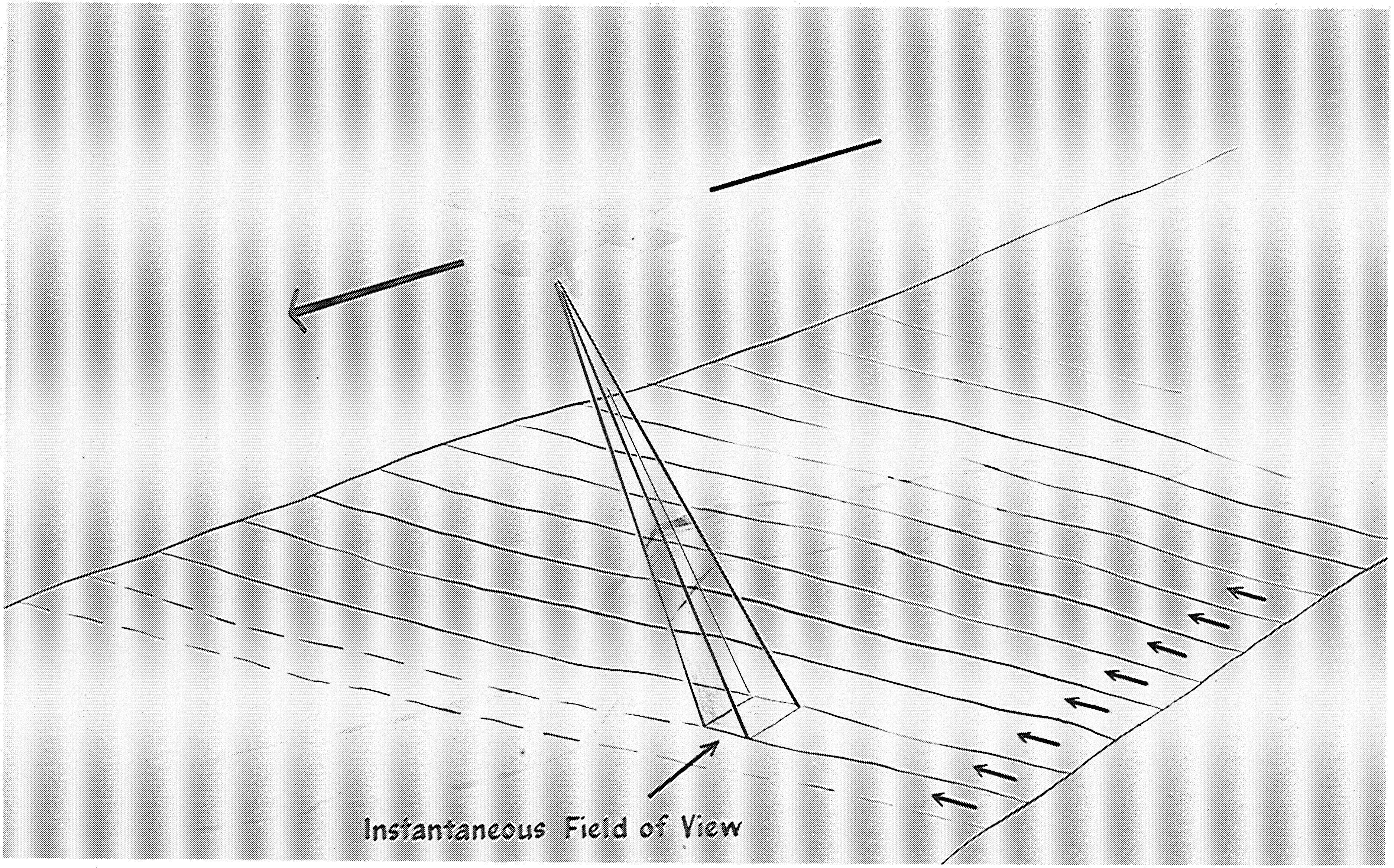


Fig. 5 One of the Many Possible Scanning Methods

piece of semiconductive material whose electrical properties change when irradiated with infrared radiation. The more infrared radiation which strikes it, the greater is the change of this property.

As the scanning system scans over and feels out the radiation coming from each small portion of the scene, a recording system usually in the form of a cathode-ray tube rescans this scene such that there is a 1:1 correspondence between points on a cathode-ray tube and points in the field. In this manner, the second transducing action occurs so that the scene is made visible. Direct viewing or visible photography can be used at this stage.

The ultimate sensitivity of the equipment will depend upon the information capacity or the rate at which signals must be passed through the detector and the rest of the equipment. It is well known that, in any system which is limited by random noise, the duration of the measurement of a signal will govern the precision of the measurement. This is simply because the random fluctuations are as much positive as they are negative so that the average value of longer and longer duration measurements tends to converge to the systematic signal value. Therefore, a slower scanning speed will make possible a greater ultimate sensitivity. The resolution will be governed by the instantaneous field of view of a small segment which is scanned at each time. If the resolution is increased by decreasing the instantaneous field of view, then a greater number of scans must be made to cover the same area. In addition, the rate at which signals change increases along each scan because there is more detail which can be received. Therefore, resolution, speed of scan, and ultimate threshold sensitivity are all inter-connected.

Spectral Response

It is well known that in visible photographic work that photographic film has a variety of spectral responses. The same can certainly be said of infrared detectors. Infrared detectors have a great variety of speeds of response, of threshold sensitivity, and of spectral response. Figure 6, taken from Aviation Week, March 1957, shows noise equivalent power as a function of wavelength for a number of different detectors. Noise equivalent power is that infrared power incident upon a detector which can be detected with a signal to noise ratio of unity when the amplifier frequency band pass is 1 cps.

You will recall that the radiation which is received at the aperture of the infrared system is already filtered and modified by the atmosphere. The response of the detector to the remaining radiation is still not 100%. In order to determine the actual usable power which is utilized at the detector, one must divide the modified blackbody curves by the spectral response of the infrared detector.

Interpretation

The interpretation of the recorded images requires a knowledge of the relationship between what has been viewed by the sensor and what appears on the recording. A certain amount of intuition can be brought to bear on the interpretation of infrared images. In one's every-day life, he has already observed some of the natural phenomenon which occur and are the results of the natural radiation exchange of our world. Out in the open on the surface of the earth, the temperatures of objects are continuously changing. If one measures temperatures of a variety of common items, one will find truly different surface temperatures depending upon all the variety of meteorological

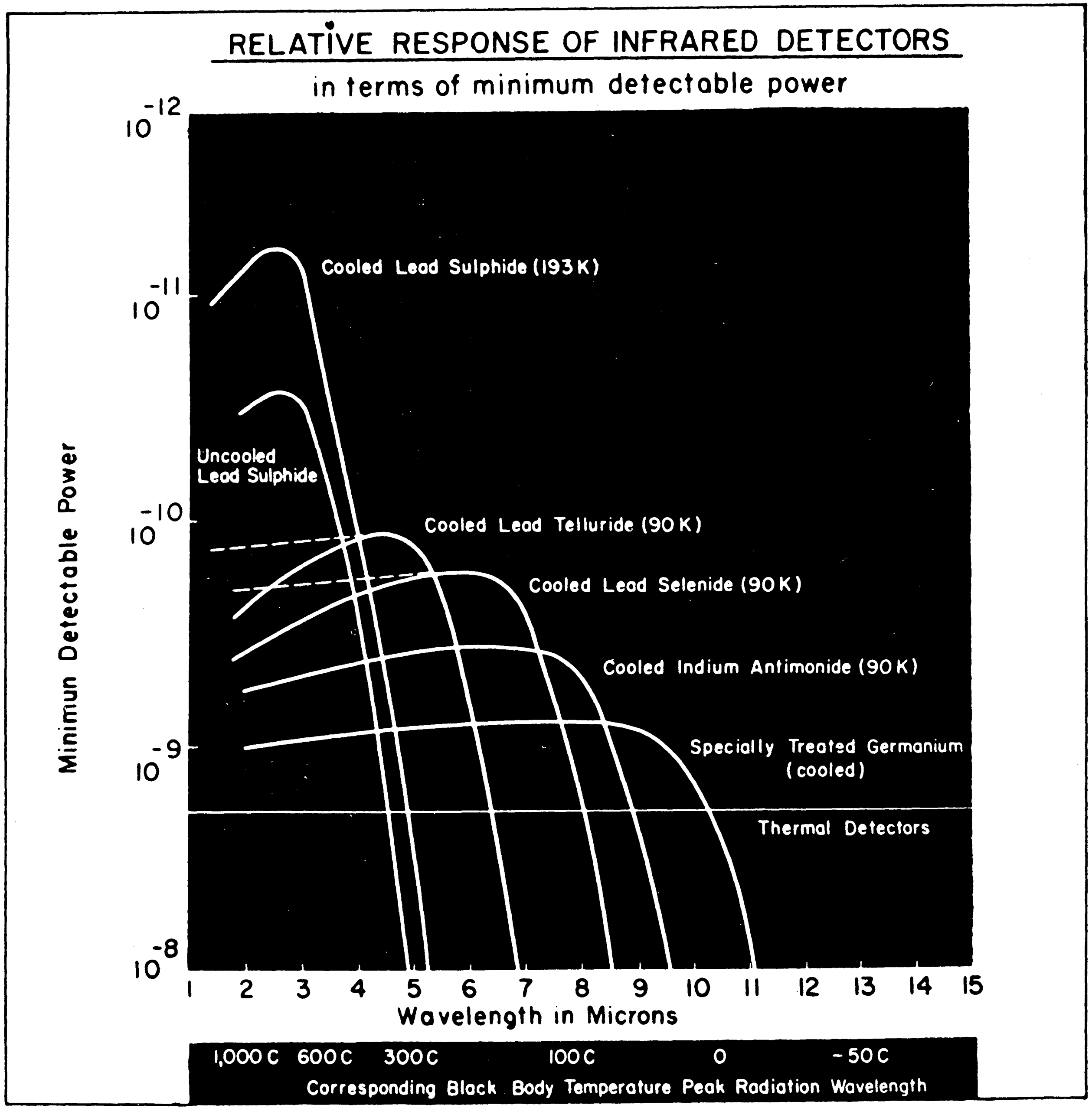


Fig. 6 Spectral Resonse of Infrared Detectors. (Aviation Week, March 1957)
Just as photographic films vary in sensitivity for different wavelengths so also do photodetectors for infrared detection. The progressively lower peak sensitivity for detectors which are sensitive to progressively longer wavelengths has a theoretical basis.

situations. Truly, a surface temperature variation does exist. In addition, surface conditions also are different. These two factors (the surface temperature and emissivity) are not entirely unrelated. The source of heat is mainly the solar radiant energy. During the day, those materials which have a high absorbance for sunlight pull in or absorb a great amount of heat. Those materials which have high reflectivity for solar radiation can pull in or absorb very little heat. The temperature that results depends, to a great extent, on the physical structure of these objects. The large concrete slab will pull in heat at a rapid rate, but the rise in temperature will slow for two reasons--one, the heat capacity of concrete roads is quite high, and two, the thermal connection with the rest of the earth is good. Grass and other light weight vegetation also may pull in heat at a good rate, but their heat capacity is very small and their contact with the heat sink of the earth is very poor. Hence, one would expect that grass temperature would follow quickly changes in ambient thermal circumstances. Water has notoriously one of the best capabilities of storing solar heat. Not only is the heat capacity of water very high, but also convection can carry the warm water away from the surface and cooler water from below can come to the surface to be warmed. The result is that a huge volume of water is heated. A considerable length of time is required to release this heat. Figures 7, 8, and 9 show sections of a night aerial photograph taken by HRB reconofax equipment (see Aviation Week, February 22, 1960).

In general, one can say that those things in nature which will dew or frost over on a cold night are the ones which will appear dark in an infrared photograph. Those objects which do not show dew or frost formations are those which will appear bright in an infrared photograph simply because dew or frost formation is a good indication of surface temperature. Now this general rule is not perfect because by artificial means, a person could produce an object which would not fall below dew or frost temperatures and yet by having a polished surface, the object could actually appear as if it were cooler. But for natural objects, things which occur in nature and reside in the weather, the emissivities are not extreme because of dust cover and weathering. On summer evenings when the sky is clear and the sun just sets, one can remember from his own experience how the dew forms on grass and on wooden lawn furniture. The place where dew forms first is the place where the heat capacity is lowest and the emissivity is substantial. The places which form dew later are those places which have a relatively higher heat capacity or a little better connection with the thermal sink of the earth. Those objects which obtain dew only very late in the evening or perhaps never, are those objects which will always appear bright in the infrared night photograph. Therefore, there is an intuitive means by which one can determine what should be seen in an infrared earth glow photograph. Notice in Figures 7, 8, and 9 that the vegetation in Central Park is cold compared to the concrete structures, which, in turn, are colder than the bodies of water. Dew formation on the grass of Central Park is probably a common occurrence. In early winter, the first ground areas which will retain fresh snow cover will also be the grass areas. Next to retain fresh snow fall are the concrete areas. Last to show the effects of winter are the bodies of water.

Figure 10 is daylight pictures which show the contrasts due to the predominating reflected solar radiation in the 1 to 3 u range.

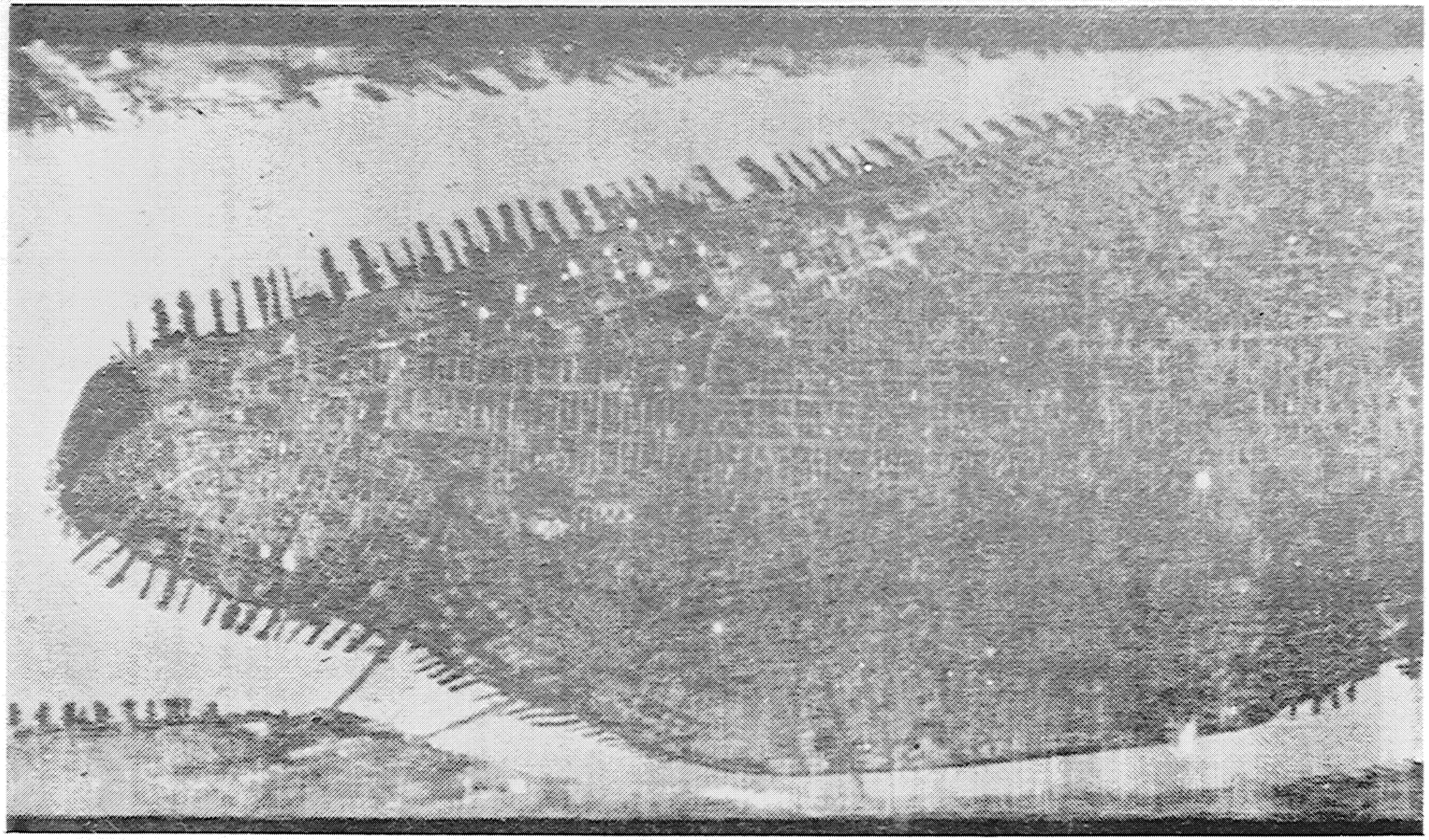


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Fig. 7 Night Infrared Photograph of Manhattan

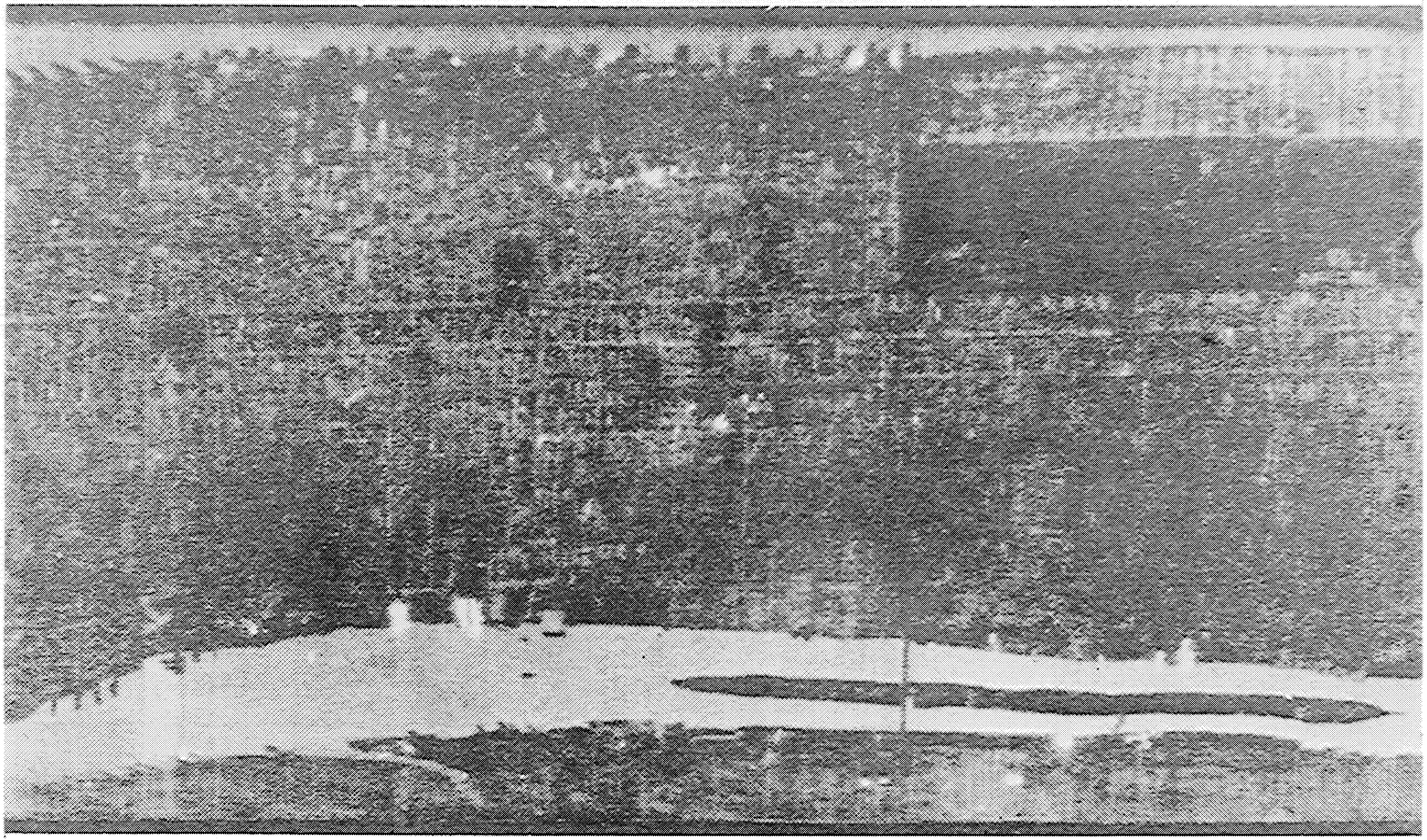

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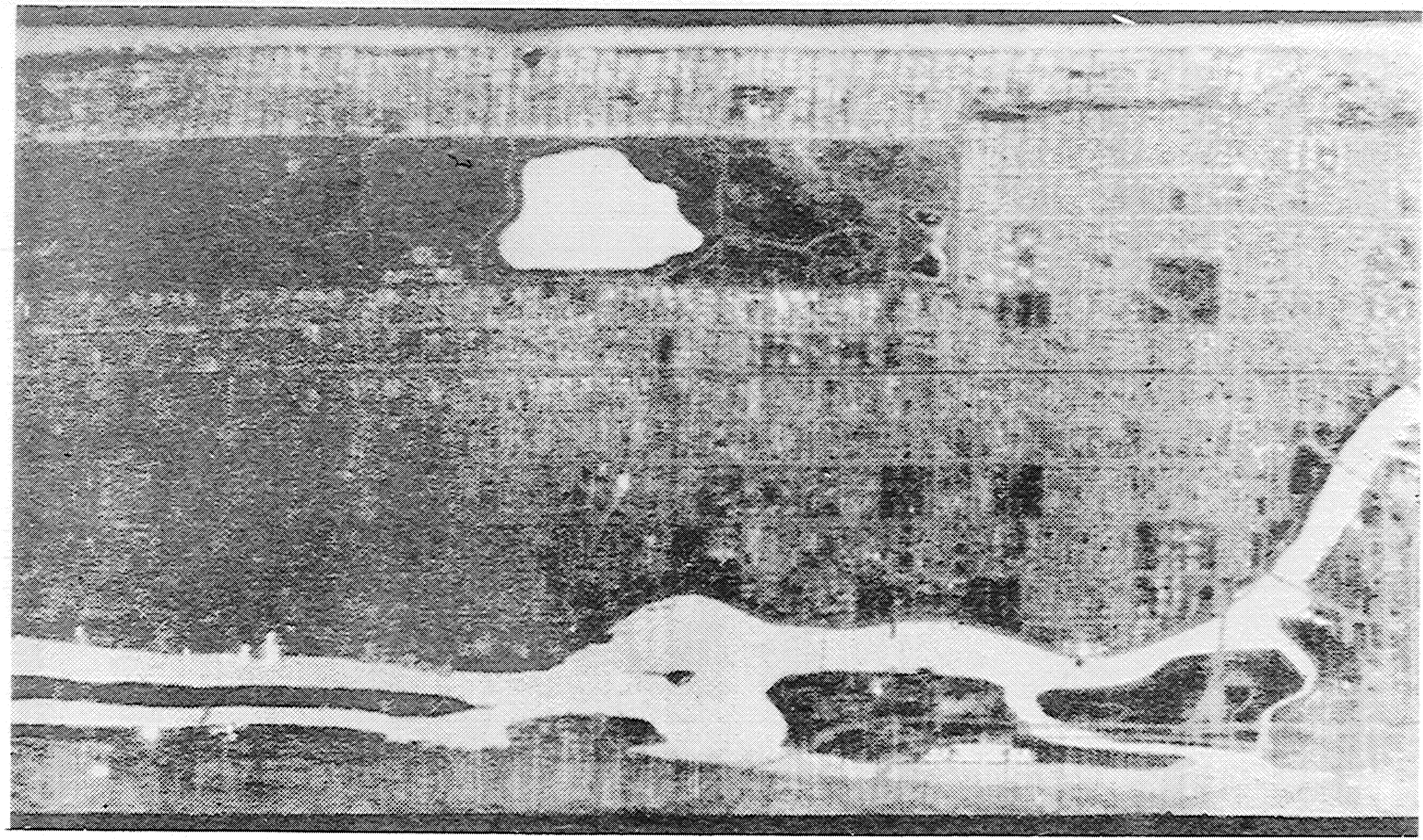
Fig. 8 Night Infrared Photograph of Manhattan



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Night Infrared Photograph of Manhattan

Fig. 10 Daytime Infrared Photograph
The effects of solar reflected radiation are dominant and provide the contrast between areas.

Longer Wavelengths

Now I have been speaking mainly of infrared radiation in the 1 to 14 u range mainly because here is the vast bulk of radiation which comprises the earth glow. This is the radiation in which we all exist and which we all radiate ourselves and which is fundamental to our existence on earth. I have neglected the longer wavelengths from 14 to 1000 u. The longer wavelengths from 14 to 1000 microns are not of great interest to long range viewing through the atmosphere because of the strong absorbing characteristics of the atmospheric gases in these ranges. This is not to say that the radiation in this range is of no scientific interest. However, as far as taking photographs of this radiation, it is of less interest because photographs are almost by definition a remote operation through the atmosphere.

Limits

In speaking further of the earth glow radiation range, there is an ultimate useful limit in the sensitivity of these devices. I mentioned that if one moves about a room or out in the open with a temperature measuring device which will record surface temperature, one will find variations well above a tenth of a degree centigrade. Suppose that we should decide to increase the sensitivity to .01 or .001^{o}C., what would be the result? One would begin to find that the expected variation simply due to air turbulence would be of the order of .01^{o}C. for small objects. A .001^{o}C. change begins to approach the magnitudes of variations in temperature which are difficult to control in laboratory conditions. Therefore, if one should have a device which is sensitive to temperature differences of only a .001^{o}C., one would find that rapid variations in temperature in a single object would occur. These variations in temperature may have no useful physical meaning.

This would certainly indicate that it is unreasonable to expect much useful information to be obtained in the .001°C. sensitivity range except under very special circumstances. Another difficulty which occurs when the temperature sensitivity is as low as .001°C., is the restriction of the possible dynamic range of the system. In analogy to the photographic film, there are only so many gray scales available. The same situation is certainly the case in the infrared system which we have been talking about. If one desires to measure the change of .001°C., then only a certain number of thousandths can be included in any record. This may allow only a dynamic range from .001°C. above ambient to 1°C. above ambient. Except under special circumstances, natural radiation in nature are much greater than this, therefore, the amount of information which can be had in the dynamic range available would be very small. It would correspond to the use of a film which has an enormous gamma and hence, things are totally black or totally white and very little is just in between. However, there is no fundamental restriction of the infrared detector or sensors which would prevent such sensitivity from being achieved. As I mentioned before, the time spent in making the measurement can be increased to such an extent that the average of the noise will be inconsequential to the average of the signal.

Summary

In summary, I have indicated that infrared radiation arises from the thermal motion of charged particles composing material bodies. The amount of radiation depends upon the temperature and the emissivity of the material. The atmosphere is also a material body which selectively absorbs as well as emits infrared.

Photography of near infrared follows an extension of standard practices while photography of earth glow radiation required special equipment.

Surface temperature differences of the order of degrees C exist as a result of the radiation exchange of our world. These temperature differences will be recorded on an earth glow photograph. A significant amount of common knowledge of surface temperature exist by virtue of observations on frost and dew formation.

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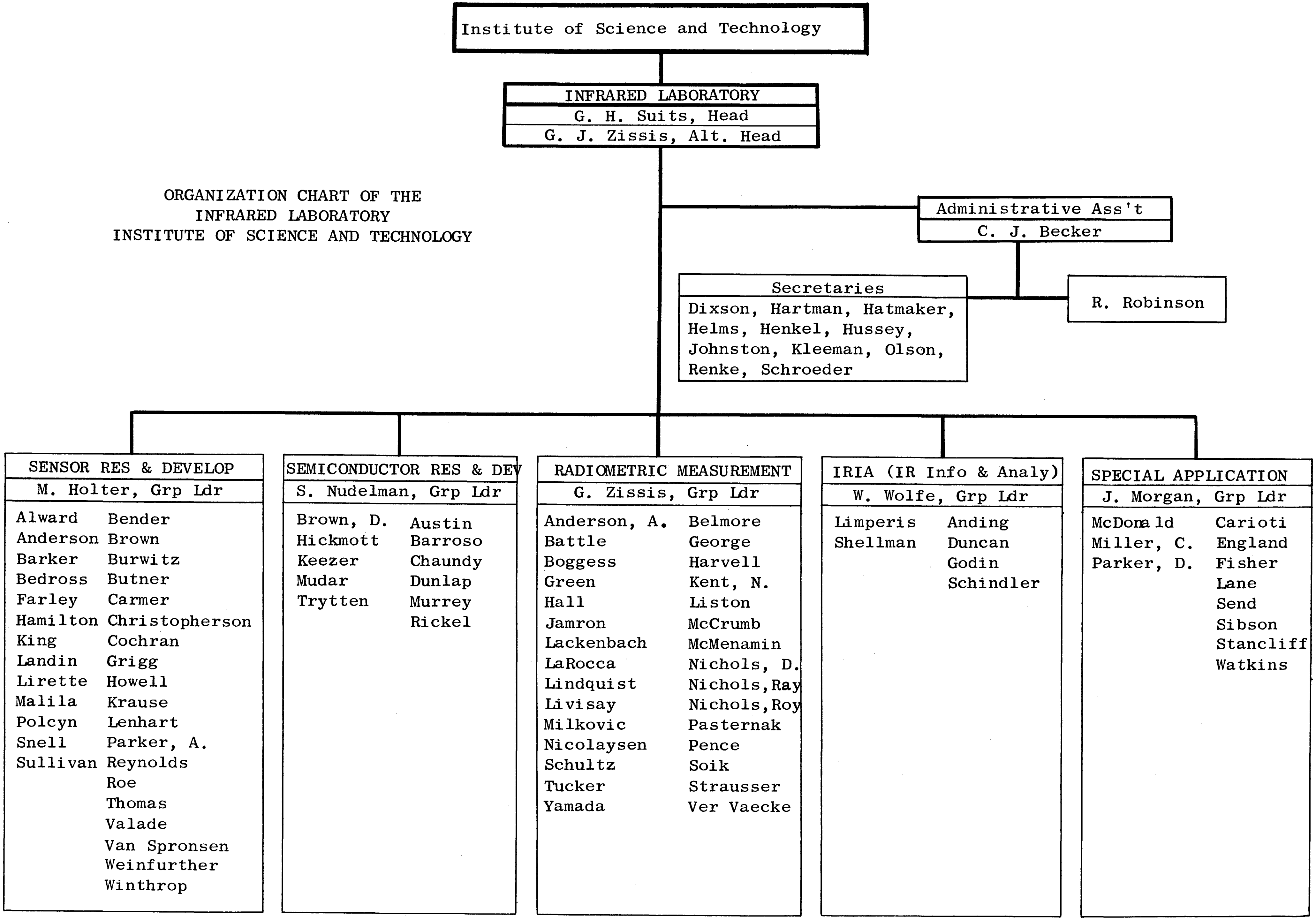

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IRIA (IR Info & Analy)
W. Wolfe, Grp Ldr

Limperis, Shellman, Anding, Duncan, Godin, Schindler

SPECIAL APPLICATION
J. Morgan, Grp Ldr

McDonald, Miller, C., Parker, D., Carioti, England, Fisher, Lane, Send, Sibson, Stancliff, Watkins

INFRARED LABORATORY CAPABILITY

The Infrared Laboratory provides a facility to undertake research in basic principles and applications of all electromagnetic radiation shorter in wavelength than the microwaves. The same type of equipment, facilities, and techniques can be used for visible and ultraviolet research problems as well as the infrared problems, and the interest of the research staff spans this broad spectrum. However, the primary support for research has been in the infrared region because of urgent military requirements, so that the current research in the visible and ultraviolet regions are negligible.

The laboratory effort is divided into five associated group efforts which are described below.

Information Analysis Group (W. Wolfe)

The Infrared Information and Analysis Center (IRIA) was established in 1955 with support from the Army, Navy, and Air Force, to ameliorate the problem of insufficient information exchange in the field of military infrared technology. IRIA makes use of the usual means of gathering scientific information; visits to industrial establishments, government agencies, and other universities; perusal of abstract journals and references; and extensive personal contact with other investigators. It also uses the somewhat unconventional techniques of electronic data processing to search for written information. Through use of these advanced retrieval techniques, IRIA is able to provide quarterly Annotated Bibliographies describing publications which have been received over a three month period; it can also provide detailed subject bibliographies on specific topics on request; it can provide advice and suggestions from the experts in the Infrared Laboratory on a wide range of infrared problems; and finally, through the use of these retrieval techniques and the knowledge of scientific investigators, IRIA can prepare reports which summarize the existing knowledge in a given field. A second important function of IRIA is the editing and publishing of the Proceedings of the Infrared Information

Symposium. This Proceedings is a national, classified journal on military infrared techniques. Other facilities of the information analysis and optical group are the extensive experience in optical components and optical properties of materials. It is anticipated that in the near future, a laboratory program for investigating unusual optical elements and interesting optical materials will be established.

Semiconductor Group (S. Nudelman)

The semiconductor group is concerned with research and development leading to improved infrared detectors and unique luminescent displays as components for sensor systems. The group has the facility and capability for making optical, electrical and galvanomagnetic measurements on semiconducting materials; fabricating new infrared detector cells and evaluating their capability; designing and fabricating dewar systems for low temperature operations; preparing special purpose phosphors for luminescent display requirements. The Semiconductor Group is supported by a well equipped materials preparation facility. Crystals are grown by a variety of methods, materials are purified and impurities added in designated quantities. Extensive evaporating facilities are available for thin film depositions. A glass blowing facility, high vacuum and low temperature equipments (down to liquid helium) provide wide experimental versatility.

Radiometric Measurements Group (G. Zissis)

The Radiometric Measurements Group performs research involving the investigation of infrared target and background characteristics; the study of calibration standards and techniques; the effects of the intervening atmosphere on infrared radiation; the analysis of data obtained by field ballistic missile radiometric measurements (all emitted and reflected electromagnetic radiation) made by workers throughout the country; and the theoretical and experimental research in fields such as the optical properties of rocket exhausts and the inter-

actions of atmospheric constituents with missiles.

The primary support for this group, at the present time, comes from the Advanced Research Projects Agency via the Air Force Cambridge Research Laboratories and consists of a project called BAMIRAC (The Ballistic Missile Radiation Analysis Center). In this project a facility has been established which functions as a technical information center on such ballistic missile phenomenology that may bear in any way on the formulation of defense measures against missile and space-vehicle systems.

Special Applications Group (J. Morgan)

The Special Applications Group is primarly concerned with the application of infrared measurement and detection techniques to new problems. The emphasis is on airborne and ground field measurement programs. IR radiometers and scanners have been used recently in such programs as the measurement of radiation from new and unusual sources and the investigation of the usefulness of such equipment in these applications. Recently, applications to Arctic research were investigated including the detection of hidden crevasses and the analysis of the structure of sea ice. Large area coverage for quantitative radiometric measurements in nature is a continuing subject of investigation.

Sensory Devices (M. Holter)

The Sensory Devices Group possesses the capability of integrating the research results of the other Infrared Laboratory groups into new sensory devices. Typical examples currently under development are: an aerial device for producing IR pictures of the ground, and an airborne device capable of detecting the presence of other airborne craft, such as might be used by the civil airlines for collision avoidance. Primary optics for infrared ommunications devices have been designed and developed recently by this group. The

application of information theory and general communication theory is made to assist in achieving optimum sensor designs.