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Thermal Infrared Remote Sensing of Surface Features for Renewable Resource Applications

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I. BACKGROUND ON THE DEVELOPMENT OF REMOTE SENSING TECHNIQUES IN THE THERMAL INFRARED

The use of thermal infrared imaging for renewable resource applications is a new and rapidly developing technique with considerable informational potential. A major obstacle to the growth of this field appears to be the lack of data specifically oriented toward renewable resource applications. From remote sensing platforms, data unrelated to defense applications is only available from meteorological satellites, the Heat Capacity Mapping Mission (HCMM) and aircraft, with the exception of a very small amount of data from Landsat-3.[1]

In the early 1970's, Landsat data became available to a potential renewable resource user community, some of whom were immediately capable of utilizing the data, others of whom gradually became aware of the potential information source and acquired the skills necessary for its use. In the past few years, that user community, which includes government, state, and municipal agencies, private industry, universities, etc., has greatly grown in size and sophistication in the use of remote sensing imagery. But this larger user community has found that the available remote sensing data is not yet completely adequate to monitor some of the major problems in renewable resource applications, such as soil moisture determinations, pollution heating effects of water and air from man's activities, mapping of sea and lake ice, snow cover mapping and run off prediction, and a host of other problems. This renewable resource community is now looking in other directions for adequate data sources, such as in the thermal infrared and microwave regions of the electromagnetic spectrum. In some cases they are looking for an additional data source to supplement the data they already have in hand; in other cases they are looking for an entirely new technique to accomplish their desired goals, such as a temperature mapping of a particular area.

The birth of thermal infrared sensing techniques started with the technical developments fostered by the Second World War. Prior to this time, except for photographic cameras, very little effort had been devoted to sensing techniques and devices to be used outside laboratory environments. The first major step in the development of thermal infrared sensors occurred with the rapid advances in electronics in the early 1940's, advances such as increased amplification, signal modulation, etc. But even in the early 1940's it became apparent that electronics was not the limiting factor in the detection process; performance was being limited by either the internal noise of the instruments, or the random external noise sources unrelated to the targets being sensed. By the 1960's, the signal-to-noise ratio problem was no longer the limiting factor to sensor development. The new sensors, however, did not necessarily solve the problems of users because they were not only sensitive to "targets" but also the the background in which the "targets" were imbedded. In the two decades of development from the the early 1940's to the early 1960's, the signal-to-random noise problem had been solved, which then had exposed a second limiting factor in the detection process, the signal-to-background noise ratio problem, some times known as the discrimination - interpretation problem.[2]

In general, three basic approaches are possible to increase discrimination - interpretation of target objects in the thermal infrared. The approaches require optimization of the signal characteristics of the object of interest by utilizing spatial, spectral and temporal effects.

For the pictorial infrared representative, the most usual form used in the remote sensing of surface features for renewable resource applications, the spatial shape of an object characterized by a fairly uniform level of infrared emission maybe sufficient to clearly identify the source of the radiation. Other areas of investigation include two dimensional optical techniques, spatial techniques featuring sample altering based on a prior knowledge of target and background characteristics, studies of analogous behavior in living organisms, and the use of reticules.

With regard to spectral identification of objects over a wide infrared window, objects of different materials can be identified by characteristic emissivity profiles, although this is more easily accomplished in certain cases by including the reflected infrared profile of a material as well as the emitted profile. Vegetation is a good example of an object which can be clearly identified under certain conditions in the wavelength region outside the infrared emission spectra and then be combined with the infrared data for greater total information content.

Temporal effects can also be used in the discrimination process. Short term effects are particularly suited to military purposes. Diurnal variations can be used to detect changes in thermal inertia and for soil moisture detection. Longer term effects such as seasonal changes can be used to detect changes in vegetation and crop growth in various stages of maturation. Again the use of thermal infrared effects for discrimination can be further aided by simultaneously gathered data from other regions of the spectra.

In the 1970's, significant sources of remote sensing data in the thermal infrared were available. The U.S. civilian meteorological satellite program was entering its second decade of operation and a wide variety of measurements were made partially through the efforts of the World Meteorology Organization (WMO) of the United Nations. As early as 1967, the WMO defined a set of goals for meteorological satellites in the global observing system of the World Weather Watch. The parameters to be observed included clouds, ice and snow, earth's surface and cloud top temperatures, radiation and heat budget data, vertical atmospheric temperature and humidity profiles, and precipitation intensity.[3] These initial parameter goals were further enlarged during the 1970's, and were monitored with increasing frequency and accuracy with the development of new satellite systems and instrumentation. Other meteorological satellite programs which continued to develop over this period were the Defense Meteorological Satellite Program (DMSP) which was started in 1966 and the Soviet meteorological program which started in February 1967; both programs have been in continuous operation since their initiation.[4]

In 1978, the Heat Capacity Mapping Mission (HCMM) produced thermal data at spatial resolutions of 600 meters for over two years, and many participating researchers in renewable resource applications are now using and evaluating this data.[5]

Another vast source of data exists from aircraft thermal infrared mapping programs. Diverse groups have produced data such as the cooperative effort between NASA/Ames, the University of California-Davis and USDA-Arizona, the University of South Dakota, the University of Kansas, Texas A&M, LARS-Purdue University (who participated in the "corn blight watch" effort), the Environmental Research Institute of Michigan (ERIM), the Canadian Center for Remote Sensing (CCRS), the Netherlands Interdepartmental Working Community for Application of Remote Sensing Techniques (NIWARS), and CSIRO in Australia.[6]

II. BASIC PHYSICAL CONCEPTS OF THERMAL INFRARED MAPPING

Four basic physical laws describe thermal infrared radiation and its relationship to the temperature or emitting bodies. The first, known as the Stephan-Boltzmann Law, states that the intensity of emitted radiation from a body is proportional to the fourth power of its temperature. A second law attributed to Wein, defines the wavelength at which the maximum output of the energy distribution occurs; that wavelength is inversely proportional to the temperature of the emitting body. A third relationship, Kirchoff's Law, states simply that if a body at a given temperature strongly absorbs radiation at a particular wavelength, it will also radiate this wavelength strongly, assuming of course, that radiation at that wavelength is present in the radiation spectrum for that temperature. Fresh snow, for example, is white because it scatters visible light incident to its surface, and therefore absorbs very little direct high temperature solar radiation; on the other hand it acts as a near perfect absorber and emitter or "black body" to the long wavelength radiation from the earth's atmosphere at lower temperature. A fourth and more general relationship derived by Planck in 1900, describes the energy distribution of emitted radiation as a function of both temperature and wavelength.[7]

The general laws stated above hold for thermal infrared radiation in all cases. For the specific conditions of satellite observations of the earth's surface however, a host of new physical concepts are operative. To start, of the 100% of solar radiation arriving at the top of the atmosphere, only about 47% is absorbed by the surface of the earth. This 47% is composed of a direct absorption of 27% of the short wavelength solar radiation with an additional indirect 20% absorption of energy which has been reflected downward or conducted through the atmosphere. On the other hand nearly 49% of the incoming radiation is immediately reflected back toward space by the earth's surface, the atmosphere and clouds, a condition which depends on the reflecting power or albedo of each of the three surfaces. The determination of albedo is fundamentally important to energy and hear balance studies of the earth and its atmosphere, and has been one of the parameters optimally determined by satellites from outside the earth/atmosphere system. Although albedo measurements are reflected rather than the thermal or emissive region of the energy spectrum, data from both infrared spectral regions are necessary to account for the budgeting of the solar radiation distribution incident at the top of the earth's atmosphere.[8]

At the earth's surface the incident solar energy is either absorbed, reflected, or transmitted. The ratios of these three surface quantities to the incident solar energy are defined as the coefficients of absorbance, reflectance, and transmittance, respectively. From Kirchoff's law, the spectral infrared absorbance of a material equals its emittance, because transmittance can be disregarded in this spectral range. Thus, a good absorber is a good emitter and a poor reflector.

The disposal of incident solar energy at the earth's surface acquires an equilibrium status described by the energy or heat balance equation. The element of this equation describing solar flux absorbed by the earth's surface depends on the solar constant, the atmospheric transmittance in the visible spectrum of the incoming radiation, the surface albedo, solar declination, latitude of the observation and the diurnal phase of the sun with respect to local noon.[9] Corrections must be made for ground slope, clouds, and atmospheric transmittance.

The element of the heat balance equation describing the outgoing energy flux from the surface includes the net infrared emittance plus the conducted and latent heat contributions. The emittance from the earth's surface varies considerably with the emissivity, ε, of the various surface materials; this emissivity is the constant of proportionality from the Stephan-Boltzmann law.

Due to the energy equilibrium at the earth's surface, the surface acquires a kinetic temperature. But the radiant temperature sensed by a detector immediately above this surface records the product of the surface material's emissivity and the fourth power of its kinetic temperature. Thus, there is a transformation between the input energy and resultant kinetic temperature of surface materials, and their emitted flux, indicative of the measured radiant temperature. Both the solar flux absorbed by the earth's surface and the output flux from this surface can be interpreted as boundary conditions to a heat flux equation. This heat flux equation with boundary conditions, in conjunction with proper conservation of energy relationships, can be solved for periodic solutions which approximate the physical situation at the earth's surface. This periodic solution describes the property of thermal inertia, loosely defined as the temperature response of a body which has been subjected to a time varying energy flux (e.g., diurnal variation of solar radiation at the earth's surface) at a surface. The typical thermal inertia curve of surface temperature with time peaks to maximum values near local noon and sinks to a minimum in early morning, a few hours after midnight. In order to assess the inflection points of this diurnally varying curve, remotely sensed observations should be scheduled to be collected over a particular geographic location at the times of maximum and minimum thermal inertia values.[10]

After the energy balance at the earth's surface has been determined, convective properties at the earth's surface-atmospheric interface must be considered. Factors which do not influence surface-atmospheric thermal infrared fluxes by reason of convective variations include the geometry of radiative properties, atmospheric transmission of radiation and earth's surface reflectivity, and variation of temperature with depth below the surface. Convection does control heat and moisture fluxes into the atmospheric microclimate through turbulent transfer processes dependent on mean wind speed (advective heating changes shown by streaking in infrared imagery), atmospheric stability, surface roughness, and the temperature and relative humidity contrasts between the earth's surface and the microclimate. In general turbulent effects in the atmospheric layer immediately above the earth's surface affects the temperature determinations made at higher altitudes.[11]

The net result of the incident energy and emitted flux transformation at the earth's surface is that the short wavelength distribution of incoming solar radiation incident to the earth's surface is transformed into a longer wavelength distribution emitted from the earth's surface. This longer wavelength distribution begins at about 3 μm and proceeds to still longer wavelengths, longer wavelengths which happen to match the beginning of the spectral region of thermal infrared radiation and accounts for a principal argument for the importance of thermal infrared sensing of the earth's surface.[12]

As the emitted longer wavelength distribution in the thermal infrared leaves the earth's surface and atmospheric interface and is transmitted through the upper layers of the atmosphere to aircraft or satellite altitudes, atmospheric effects are encountered. Gases and suspended particles may absorb the radiation, resulting in a decrease in energy reaching a solar sensor. Attenuation of the original signal can also occur due to atmospheric scattering. Gases and suspended particles in the atmosphere also emit radiation of their own. The net result is that atmospheric absorption and scattering tend to make the ground emission appear at a colder temperature; atmospheric emission makes the ground emission appear warmer. Although these perturbations bias the sensor output, the readings can be adjusted.[13] Both the artificial warming and cooling effects are a function of the atmospheric path length and direction of path through which the radiation passes, because the gases and particulates causing the perturbations lie in bounded layers throughout the atmosphere.

From the point of view of designing a satellite mission to measure renewable resource applications, the thermal inertia observable described above is a physical property highly sensitive to the thermal infrared measurements as contrasted with a reflected infrared, a passive, or an active microwave experiment. Even so, the thermal inertia observable for bare soil, for vegetation, or for combinations of bare soils and vegetation, represent three distinctly different interpretations of the same parametric value, even in the thermal infrared. For the bare soil case, both the heat capacity and the thermal conductivity of soil increases with the increasing soil moisture, producing a resulting increase in the measurable thermal inertia. Surface evaporation is a complicating factor which reduces the solar energy input to the soil and the difference between maximum and minimum diurnal temperature variations. There is, however, a good correlation of soil moisture down to 4 cm depth with thermal inertia. Initially, when a soil surface is moist, soil temperature values vary strongly with evaporation, but for dryer soils, temperatures can be determined by thermal inertia. In comparison, for a bare soil moisture determination from reflected infrared rather than thermal infrared radiation, the soil spectral reflectance as a function of water content cannot be isolated because of the spectral reflectance of dry soil, surface roughness, geometry of illumination, organic matter, and soil texture. For the vegetative surface case, thermal infrared measurements of the vegetation canopy temperature minus ambient air temperatures can be used to determine soil moisture stress in growing vegetation; reflected infrared radiation is an isotropic as a function of the geometry of the local orientation, and is highly sensitive to the angle of incidence and viewing angle.

On the other hand, both passive and active microwave approaches to sensing of the earth's surface are similar in that they both can penetrate clouds and moderate amounts of vegetation and they sample soil depths to 2 to 5 cm. The spatial resolution for passive microwave measurements is a function of the size of the antenna, but is on the order of 10 km, marginal for many renewable resource applications. Active microwave techniques include the use of synthetic aperature radars and can produce spatial resolutions of 100 meters or better, but other problems such as obtaining an absolute calibration of the instrument, strong sensitivity to the viewing angle and surface roughness, and the large data to be handled in an operational mode somewhat compromise the high resolution advantages.[15]

In summary, thermal infrared imagery of thermal inertia is a good indicator of surface properties such as soil moisture, for example; data can be obtained at high spatial resolution, but is highly sensitive to transmission through the atmosphere. Because thermal infrared radiation is caused by transitions between molecular vibrational and rotational states, absorption by atmospheric gas molecules is a serious problem, especially by water vapor and carbon dioxide molecules in different densities in the layered atmosphere. This problem can be overcome by looking at the earth's surface through different atmospheric transmission windows, such as the 10.5 to 12.5 μm region. Microwave measurements penetrate clouds in the atmosphere and the earth's surface, but do have problems of either spatial resolution, or sensitivity to the measurement at the observable alone without other variables affecting the measurement. Reflected infrared detection of soil moisture has extreme disadvantages because of its dependence on so many variables, and as a result it is useless as an indicator of specific observables, such as soil moisture. The physical properties detected in the reflected infrared, thermal infrared and microwave regions of the spectra are vastly different and require dissimilar instrumentation and detection techniques.

III. STATUS OF TECHNOLOGY

The precision and accuracy that can be achieved in radiometric measurements are limited by the very nature of thermal infrared radiation and also by the fact that radiant power is distributed and may vary simultaneously with a number of different parameters. For example, every particle of matter involved in a thermal infrared measurement may be radiating and/or absorbing and/or scattering radiation, which includes molecules of gas along the optical path, and the supporting structures of the measurement instrument itself. The distributions of radiant power and its interactions with matter is a function of its wavelength, position, direction, modulation frequency of fluctuation in the level of radiant power, and polarization.[16]

In a field measurement, a radiometric instrument is usually surrounded by radiation flowing past it in all directions, the unwanted radiation can usually be reduced to acceptable limits in laboratory measurements in the visible spectral region by use of high quality optical systems with clear transmitting elements, highly reflecting and well polished mirrors, and dead black opaque stops and baffles. Such an optical system of precision dimensions can produce sharp, isolated, well defined beams. For the longer wavelengths of the infrared spectral region, however, new problems arise. For example, ambient temperature from the structural components of the instrument may produce random thermal emissions above specified tolerance levels which requires instrument cooling and all its related complications. Optical design of thermal infrared systems, even though implemented by complicated ray tracing computer programs, must contend with larger optical systems than those in the visible spectral region. Transmission, reflection, or non-reflection characteristics of optical systems may also be difficult to obtain.[17]

Another essential element of a radiometric instrument is the detector element or transducer which transforms quantities of incident radiation into a measurable quantity, such as electrical conductance. In the thermal infrared spectral region, unlike the visible region, detector spectral detectivity curves measured by D* values, the reciprocal of the spectral noise equivalent power, vary dramatically with wavelength and temperature. This has resulted in the production of a large number of detector elements, composed of different materials, cooled by different systems to various temperature levels, each designed for specific uses in narrow pass bands in the infrared spectral region.[18]

An amplifier or output indicator, usually electronic, is the third basic element of a radiometric instrument system. The current status of electronic development makes this a very strong and reliant part of the system, unless new technology is being developed such as multilinear array technology. Amplifier design is facilitated by producing an AC rather than a DC output from the detecting element. Choppers may be employed to reduce drift problems which occur in DC instruments.

In general, the ideal radiometric instrument has an optical system with no vignetting or aberations, so that field and aperature are sharply defined, independently of one another at all wavelengths. The instrument responds uniformly to all wavelengths in a spectral band and to none outside the band, and likewise, responds uniformly to all polarizations within sharply defined intervals of polarization parameters. The radiometric system is completely linear so that the final output is directly proportional to the incident radiant power (within the aperature and field of view) throughout the entire dynamic range of measurement values. Linearity extends to temporal frequencies present in any levels of incident radiant power, i.e. an integral of the output over any time interval corresponds to the total energy incident in that interval.

When the ideal of constant responsivity throughout the range of each parameter is not realized, then instruments should be designed with separable responsivity transfer functions, where each parameter's effect is independent of all others. If this is achieved, then the responsivity function of all significant parameters can be written as a product of independent one parameter functions. This, of course, greatly reduces the problems involved in calibrating the instrument.

Finally, after all improvements in instrument design and manufacturer have been accomplished, there remains a noise equivalent input radiation or temperature, NEΔT. The overall goal of instrument design is to keep the instrument noise level well below the measurement signal level to avoid interference or distortion in measurement. Failing this, the order of magnitude of the system noise level must be assessed and its interfering factor on measurements evaluated.

The status of infrared technology from satellite platforms is most easily assessed by looking at meteorological satellite systems. For infrared mapping type functions, two types of radiometers have been used, infrared radiometers with medium resolution, MRIRs, and those with high resolution, HRIRs. The MRIRs have had optimal linear spatial resolutions of 64 km and the instruments flown on TIROS, Nimbus, or the Soviet Cosmos have all usually been multiband instruments. The HRIRs instruments have been primarily dedicated to facilitating night mapping of the earth's cloud cover and more extensive measurements of cloud top and earth surface temperatures. These radiometers characteristically have had 8 km resolution, from orbital altitudes of 1100 km, and generally operate in the 3.5 to 4.1 μm atmospheric window.

Two types of infrared radiometers were first used on Nimbus III satellites, the Satellite Infrared Spectrometer (SIRS) and the Infrared Interferometer Spectrometer (IRIS). Both of these instruments were used to determine vertical soundings through the atmosphere, but also provided a mapping capability for ground surface temperatures at a medium spatial resolution of 100 km. The SIRS is a multichannel radiometer which views a number of spectral bands simultaneously; the IRIS is a scanning interferometer with wave number spectral resolution in the 5 to 26 μm range. Both the SIRS and the IRIS provide significant thermal infrared data about the atmosphere over the "target", allowing earth surface temperature determinations for renewable resource applications to be calibrated and interpreted more accurately.[19]

Higher spatial resolution, in the 1 km range, was achieved by the Very High Resolution Radiometers (VHRR) flown on the NOAA satellite series through NOAA-5. These NOAA satellites were launched into near polar sun synchronous orbits at 1500 km altitudes. Equatorial images are acquired twice daily, one in the day and one at night. At high latitudes around the polar regions, NOAA orbits converge producing a greater number of images per day, both in the broad visible band, 0.5 to 0.7 μm, and in the thermal infrared 10.5 to 12.5 μm band.

NOAA-6 or TIROS-N is a third generation satellite series and an improvement over the NOAA series through NOAA-5. TIROS-N introduced a new infrared instrument, the Advanced Very High Resolution Radiometer (AVHRR). The initial four channel flight instruments, still at 1 km resolution, have infrared channels at both 3.55 to 3.93 μm and 10.5 to 11.5 μm. These channels are designed to measure cloud distributions and to determine temperatures of either cloud or surface radiating surfaces. These two channels will also contribute to the computation of sea surface temperatures. But only with data from a second version, AVHRR/2, five channel instrument with split channels at 10.3 to 11.5 μm and 11.5 to 12.5 μm, will the radiance from water vapor be deleted from surface temperature measurements.[20] Beside the U.S. Meteorological Satellite Program, developments have progressed in both the international programs under the World Meteorological Organization as well as the U.S. Defense Meteorological Program (DMSP).

Two other meteorological satellite programs bear mentioning. The Earth Radiation Budget Experiment (ERBE) was devised to overcome previous deficiencies in earth radiation budget measurements. Two TIROS-N/NOAA satellites combined with the ERBS satellite, provide an even distribution of spatial and temporal coverage, permitting more precise measurements and calculations of average monthly components of the radiation budget.[21]

The geosynchronous satellite program was begun in May 1974, with the launch of the Synchronous Meteorological Satellite (SMS-1). The SMS-1 carried an instrument with a 16-inch aperature telescope, the Visible and Infrared Spin Scanning Radiometer (VISSR), from which data was collected on clouds in both day and night, atmospheric temperatures, cloud heights and wind fields. SMS also collects data from other conventional instrumentation such as river gauges, ocean buoys, ships, balloons, and aircraft. Other satellites in the series are SMS-2 (1975), Geostationary Operational Environmental Satellite (GOES-1) (1975), GOES-2 (1977), GOES-3 (1978), and GOES-4 (1980).[22]

Starting with GOES-4, these geostationary satellites will carry VAS, Visible Infrared Spin-Scan Radiometer which is an advanced version of VISSR. The VAS is a dual band imager like VISSR, but its infrared channels have greater utility with expanded detector configurations and selectable narrow band optical filters.

The new channel capabilities of VAS provides sensitivity to atmospheric constituents which allows the determination of the three dimensional structure of the atmospheric temperature and water vapor distribution.[23]

Moving away from the meteorological programs, the Heat Capacity Mapping Mission (HCMM) has provided the next highest thermal infrared spatial resolution to date, 0.6 km by 0.6 km at nadir. The orbital altitude of the spacecraft is 620 km and it is the only system specifically dedicated to thermally mapping the earth's surface, the primary focus of this paper. Many investigators are now processing and evaluating the HCMM data, and a variety of renewable resource applications will be mentioned in the next section. By comparison, the Landsat-3 achieved an even higher spatial resolution, 240 meters, in the thermal infrared than the HCMM, but the temperature accuracy of the measurement, indicated by the noise equivalent temperature, NEΔT, was worse by a factor of 3, and has little utility for renewable resource applications which require absolute temperature data fidelity.[24]

Finally, a new technology is being developed for the thermal infrared and other spectral regions, Multi Linear Arrays (MLA). MLA's are fixed linear strings of solid state detectors which accept radiation continuously while over a target, eliminating the "dwell time" factor of a scanning mirror type assembly used in the Multi Spectral Scanner (MSS) and Thematic Mapper (TM) of the Landsat series. These linear arrays or push broom scanners are moved to the next scene track simply by the forward motion of the satellite, eliminating the liabilities of noise, power requirements, instrument life time, and mechanical reliability of a physically scanning mirror drive assembly.

IV. APPLICATIONS TECHNOLOGY

The number of actual scientific studies in which thermal infrared data has been used for renewable applications is rapidly growing and the HCMM program has given a considerable push to studies using thermal data from satellite platforms.

When all corrections to thermal infrared data have been made, the data remaining represents a thermal mapping of the earth's surface terrain. New applications for surface information alone, obtained from thermal mapping, have progressed rapidly in the last few years, and a brief reference to some of those new applications will be made here.

A soil moisture determination from space data is one of the most desirable application potentials from both the agriculture and water resources points of view. Some of the specific agricultural applications, listed by the Soil Moisture Workshop held in January 1978 in Beltsville, MD, include drought, crop, range and forest production, pest management, soil classification, and wetland inventory. The hydrological applications include determinations of runoff potential, erosion losses, reservoir management, infiltration, and water quality. Ground hydrologic modeling data to be used as inputs into climate models represent another distinct application requirement. Agency and organization uses were also outlined by the Soil Moisture Workshop.

A thermal infrared approach using frequently obtained data from either the HCMM or a GOES satellite hold the most hope for soil moisture determinations, because currently, thermal infrared techniques are more advanced than those of microwaves. A recent survey of the status of techniques for determining soil moisture has been published by Schmugge et al. and an older Canadian survey of thermal infrared techniques for the determination of soil moisture, evaporation and evapotranspiration, and plant stress was given by J. Cinlar and A. K. McQuillan. A paper by D. S. Kimes et al. has investigated the relationship of thermal infrared radiances and agronomic variables of plant canopies, which include plant water stress.[25]

HCMM investigators have also contributed studies relating thermal infared mapping to agricultural and water resources applications. A Texas A&M study relates dryland pasture and crop conditions to HCMM data as an extension of other projects, undertaken in cooperation with GSFC on the subjects of wheat yields, green biomass, and watershed run off coefficients; using visible, near and thermal infrared, and passive microwave data.[26] A thesis from the Penn State Meteorology Department combines a numerical simulation of the ground temperature response and satellite measurements of surface temperature to deduce soil moisture availability or the amount of surface moisture. This data, taken over a watershed in Missouri, is related to the type of surface areas which include croplands, forests, creeks and small urban centers.[27]

One other HCMM soil moisture investigator is the Commission of European Communities Joint Research Centre, ISPRA Establishment, Italy. Researchers from Great Britian, France, West Germany, Italy, etc. are participating in the Tellus Project which uses HCMM data to produce soil moisture and heat budget evaluations in selected European zones of agricultural and environmental interests. This HCMM group investigator has produced a soil moisture model and a number of papers from investigators of different nationalities on agricultural and environmental subjects to be detected by thermal infrared surface mapping.[28]

Another high potential land use application of the thermal infrared data with suitable spatial resolution relates to the environmental effects of urbanization. The reflecting and radiating characteristics of regions which have been urbanized have been altered in the replacement of soils, grass, and trees by brick concrete, glass, and metal surfaces at different levels above the ground. Another effect of man's activities has been the generation of heat by means of combustion and metabolic processes. This phenomena is usually associated with urban areas in mid-latitudes; in Hamburg, for example, the average production of heat from coal combustion has been estimated at 40 cal/cm^2, compared to the total radiation from the winter sun and atmosphere combined of 42 cal/cm^2.[29] A third effect produced by urban centers is the modification of the local atmosphere by the emission of vast amounts of gaseous and solid pollutants into the air. The original work of H. Landsberg in 1961 predicted, among other things, the formation of the urban heat island which acts as a trap for atmospheric pollutants[30]. One study using HCMM data and a boundary layer model, a thesis from the Meteorology Department of Penn State, addresses the problem of surface characteristics and the energy budget over an urban-rural area.[31]

Another application of thermal infrared imaging is the mapping of sea and lake ice, which has been considered in a number of studies with estimates of ice thickness. For example, Kuhn et al., used an airborne thermal infrared sensor over an area with only 3.0 cm of snow cover and were able to predict ice thicknesses between 9 and 110 cm, with rms differences of 10 cm.[32] Varying depths of snow cover on an ice surface were also detected in the thermal infrared by Cihlar and Thompson; while in another study by Poulin, snow depths covering a uniform ice thickness were measured to depths of 50 cm.[33] In another larger study, Poulin investigated thermal infrared imagery response over a wide variety of artic terrain, and made a number of conclusions on the usefulness of the data.[34] Other investigators, Schertler et al., have found thermal infrared data useful for mapping lake ice, and that the data usually allows designation of ice types, representing the combined effects of ice roughness, thickness, snow thickness, snow distribution, etc.[35]

Thermal infrared imagery can also be used in applications dealing with snow cover mapping and run off prediction. Seifert et al. studied the combined use of visible and thermal infrared data on snow covered areas, although extensive use has been made of visible-near infrared data by Rango and other Landsat users.[36] NOAA thermal infrared data can be used to map the extent of snow cover in most cases, as Barnes et al. have shown, but snow boundary thermal gradients are more easily detected in spring than winter.[37] Another study by Algazi and Suk found some correlation between snow pack temperatures based on ground based measurements and those determined from NOAA satellite data.[38]

At the present time, J. Barnes is an HCMM program investigator and is studying the utility of using HCMM data to determine the distribution of snow cover and the accuracy of temperature measurements. Two other goals of his study are to combine HCMM and Landsat data into an overall snow hydrology and snow melt prediction program and to develop a technique to automate HCMM and Landsat data in a format useful for snow hydrology research.[39]

The detection of sea and inland water pollution represents another application of thermal infrared imagery. Not all the types of water pollution listed are independant variables. For example, temperature plays an intrinsic role in chemical and biological reactions. Bacterial action is greatly accelerated at higher temperatures, and can substantially affect the self purification of streams. Warmer water also speeds up anerobic decomposition, producing far reaching effects on a stream's overall health from heat alone, aside from the heat's more direct impact on fish and wildlife.

The chief source of thermal pollution at the present time is from electric power generating plants, with additional thermal pollution from chemical, steel, and pulp and paper processing plants. A number of studies have been conducted on the effects of thermal pollution. Pluhowski has studied the effects of urbanization on the streams on Long Island, New York, documenting the impact on runoff and temperature from changes in infiltration in clearance of vegetation from the channels, in small impoundments in different reaches, and in land use adjacent to the channel.[40] A study by Taske and Goebel on the effect of the large reservoir system on the Columbia River, Washington, showed that reservoirs tend to reduce temperature variability.[41] But the thermal effects cited in these studies are still small compared to the potential for temperature increases caused by heated discharges of cooling water from power plants, as treated in a review by Jensen.[42]

Some investigators are currently studying thermal patterns in water bodies from HCMM data. More et al., from South Dakota State University use the data as an input for assessing regions of high potential ground water pollution.[43] British investigators Fielder and Tefler are using HCMM data with that of visible and near infrared to determine marine pollutants, particularly oil, on the North Sea surface.[44] A study by Nilsson et al. observes the Tasman Front of the coast of Australia with HCMM thermal infrared data. The study attempts to identify a postulated broad zonal sea flow of 500 km width, fed by the East Australian current, which crosses the Tasman Sea at 35° South latitude.[45] A French team, P. Y. Deschamps et al., are using HCMM data to study the sea surface temperature off the coastal zones of France. The goal of the study is to map the thermal gradients in the French coastal zone produced by natural phenomena and man-made thermal effluents.[46]

Other applications of thermal infrared mapping have been discussed by Cihlar and McQuillan. They include the mapping of: perma frost and frost prone areas, buried ice fields below the earth's surface, thermal characteristics of ecosystems for animal habitat assessment, thermal characteristics of biological or ecological land classification types, and forest fires. Of all these applications, only forest fire mapping requires constant monitoring and the use of geosynchronous satellite capability.[47]

From the obviously diverse nature of the renewable resource applications listed above, data interpretation, especially with regard to informational content, can be seen to be different for each specific application. This is not only a problem for the individual researcher, but it is also a problem for the satellite mission designer who must incorporate the diverse needs of many application requirements. When an evaluation of the HCMM investigator's research has been properly completed, a set of mission requirements may then be possible.

In summary, data interpretation and subsequent satellite mission requirements for thermal infrared mapping of renewable resources include a variety of possibilities. Some thermal scanning operations for geologic and soil mapping characteristics are qualitative, not quantitative in nature, for example, requiring relative radiant temperature differences in a scene rather than absolute ground temperatures and emissivities. Mapping variations in water temperatures from power plant cooling effluent is an example.

Another factor influencing data interpretation is the time of day of data acquisition. Temperature extremes, and heating and cooling rates can furnish significant information about the type and condition of an object. For example, water has a smaller diurnal range of temperatures than soil and rocks and reaches its maximum temperature an hour or two after these solid terrain materials, due to water's high thermal capacity, or ability to store heat. Shortly after dawn and near sunset, the diurnal temperature curves for water and terrain features cross, showing no radiant temperature differences between a wide range of dissimilar materials.

Throughout the day, sunlight differentially heats objects according to their thermal and absorption characteristics, principally in the visible and reflected infrared spectral regions. Reflected sunlight can affect infrared imagery in the 3 to 5 μm band. The 8 to 14 μm band is immune from reflected radiation, but thermal shadows caused by the shading of trees, buildings, and topographic features are included in infrared imagery. Sloping terrain also causes differential heating with south slopes heated more than north slopes. Predawn imagery provides the most stability for the detection of ground temperature effects and signature extension, but poor visibility for terrain identification.

Other distortions must be considered in the interpretation of thermal infrared scanner imagery, such as the geometric factors of tangential scale distortion corrections, resolution cell size variations, one dimensional relief displacements, and flight parameter distortions. Calibration problems included airborne radiometer and internal black body source referencing, air to ground correlations, repetitive site coverage, and temperature mapping from radiant thermal infrared imagery when absolute rather than relative temperature data are required for a particular renewable resource application.

V. CONCLUSIONS AND RECOMMENDATIONS

With the conclusion of HCMM data, the lack of at least one continuous source of thermal infrared imagery from a known data processing facility is the single greatest deterrent to the use of thermal infrared data for renewable resource applications. This deterrent is considerable not only for those researchers who are actually using remotely sensed data for renewable resources, but especially for the vast number of potential users who are unaware of the possible informational content of thermal infrared imagery for those applications.

The principal recommendation of this paper is that such a thermal infrared data source capability, such as that which had been provided by HCMM, be initiated. The mission parameters of such a dedicated renewable resource satellite system, concentrating on mid-latitude regions exclusively, should follow HCMM characteristics in general. Corrections or additions to HCMM mission parameters can be made when the final results of renewable resource investigators using HCMM data become available and are evaluated. Other applications requiring continuous monitoring coverage can use existing or planned GEOS systems designed principally for meteorological systems, such as the ATS/GOES.[48] Such applications include monitoring of power plant effluents, urban heat islands and heat pollutant concentrations, forest fires, etc. The ice and snow detection applications discussed above require satellite platforms orbiting over polar latitudes. Such platforms are already available within the American meteorological satellite system.

A second recommendation of this paper is that basic physical research essential to the interpretation of thermal infrared sensing of renewable resources should accompany thermal infrared satellite monitoring to form a cohesive program. Foremost areas of research should include the interaction of the earth's surface layer with the solid earth layers immediately below it, as well as the interaction of the earth's surface layer with the atmospheric boundary layer immediately above it. Additional research is also needed to assess the incremental increase in renewable resource information which can be obtained from thermal infrared sensing alone, as well as the increased information which results from combining thermal infrared data with those data from other spectral regions. Only with a firm grip on an understanding of the available tools for the gathering and processing of thermal infrared data for renewable resource applications and the resultant informational content which can be derived from these data, can meaningful future renewable resource planning proceed.

From even the brief description of the previous uses of thermal infrared imagery for renewable resource applications stated in this paper, the increased use of such imagery in future years seems inevitable. Thermal infrared mapping data, even more than some other spectral regions, provides a unique and valuable data source for a myriad of applications. Thermal infrared data combined with data from other spectral regions can greatly enhance the informational content of remote sensing imagery for many specific uses. All in all, thermal infrared sensing has been developed over a number of years, many of its problems in detection and data interpretation have been solved, it represents a unique or complementary data source for renewable resource applications, and as soon as the opportunities for its further use are available, its future increased growth rate is assured.

References

1. For a recent summary of meteorological satellite instrumentation and missions, see L. J. Allison, ed., A. Schnapt, B. C. Diesen, III, P. S. Martin, A. Schwalb, and W. R. Bandeen, "Meteorological Satellites," National Aeronautics and Space Administration TM 80704 (Greenbelt, MD: NASA/Goddard Space Flight Center, June 1980), 71 pp. Table 1 is taken from this report. For a description of the HCMM satellite, see NASA/Goddard Space Flight Center, "Heat Capacity Mapping Mission (HCMM) Data Users Handbook for Applications Explorer Mission-A (AEM)," NASA (Greenbelt, MD: NASA/Goddard Space Flight Center, February 1978), 120 pp. Table 2 presents a summary of selected thermal infrared research programs using aircraft platforms and was kindly provided by Samuel N. Goward of NASA/Goddard Institute for Space Studies, 2880 Broadway, New York, N.Y. 10025.

2. R. R. Legault, "Discrimination Introduction" notes in the University of Michigan Engineering Summer Conferences Advanced Infrared Technology: An Intensive Short Course. University of Michigan No. 95/6910 (Ann Arbor: University of Michigan, June 9-13, 1969).

3. United Nations, World Meteorological Organization, "The Role of Meteorological Satellites in the World Weather Watch," World Weather Watch Planning Report No. 18 (Geneva: World Meteorological Organization, 1967), 38 pp.

4. E. C. Barrett, Climatology from Satellites (London: Methuen & Co. Ltd. 1974), p. 22, and Allison, et al. "Meteorological Satellites," pp. 25-42.

5. NASA/GSFC, "HCMM Users Guide." 120 pp.

6. Personal communication with Samuel Goward, Columbia University and Goddard Institute for Space Studies, New York, N.Y.; see reference 1 and Table 2. For the LARS - Purdue Corn Blight Watch Experiment, see R. B. MacDonald, Marvin E. Bauer, R. D. Allen, J. W. Clifton, J. D. Erickson, D. A. Landgrebe, "Results of the 1971 Corn Blight Watch Experiment." (Ann Arbor, Mich.: Environmental Research Institute of Michigan, ERIM (October 2-6, 1971): 157-190.

7. For a general applied discussion of the basic physical concepts of thermal infrared physics, see William L. Wolfe, Ed., Handbook of Military Infrared Technology, (Washington, D.C.: Department of the Navy, Office of Naval Research, pp. 4-30.

8. R. G. Barry and R. J. Chorley, Atmosphere, Weather and Climate. 2nd ed. (London: Methuen & Co. Ltd., 1968) p. 51.

9. John C. Price, "Thermal Inertia Mapping: A New View of the Earth," Journal of Geophysical Research 82 No. 18 (June 1977): p. 2585.

10. Ibid., pp. 2582-2585.

11. Ibid., p. 2584. For a discussion of the processes at the earth's surface - atmospheric interface, see standard texts such as R. E. Munn, Descriptive Micrometeorology (New York: Academic Press, 1966), 245 pp. or R. Geiger The Climate Near the Ground (Cambridge, Mass.: English Translation from

the German by Harvard University Press, 1959), 494 pp. Advective changes shown by streaking in the imagery can be visualized by observing the streaking in aircraft imagery at different altitudes, shown in Floyd F. Sabins, Jr., Remote Sensing Principles and Interpretation (San Francisco: W. H. Freeman and Co., 1978), pp. 142 and 144.

12. See the spectral distributions of solar and terrestrial radiation and the wavelengths in which the atmosphere absorbs radiation at three altitudes in Barry and Chorley, Atmosphere, p. 31.

13. Minimization of atmosphereic effects for the 3.4 to 4.2 μm band is discussed by V. G. Kunde, "Theoretical Relationships between Equivalent Blackbody Temperatures and Surface Temperatures Measured by the Nimbus HRIR Radiometer," NASA SP-89 (Greenbelt, MD: NASA/Goddard Space Flight Center, 1965), pp. 23-37. Minimization of atmospheric effects for the 8 to 12 μm band is discussed in D. Q. Wark, G. Yamamoto, and J. H. Lienesch, "Methods of Estimating Infrared Flux and Surface Temperature from Meteorological Satellites," Journal of the Atmospheric Sciences (1962), pp. 369-84.

14. For a survey and comparison of reflected infrared, thermal infrared, and active and passive microwave techniques for remotely sensed determination of soil moisture, consult T. J. Schmugge, T. J. Jackson, and H. L. McKim "Survey of Methods for Soil Moisture Determination," NASA TM 80587, (Greenbelt, MD: NASA/Goddard Space Flight Center, November, 1979), pp. 26-40. For a more detailed analysis of temperature measurements of plant canopies, see D. S. Kimes, S. B. Idso, P. J. Pinter, Jr., R. D. Jackson, and R. J. Reginato, "Complexities of Nadir-Looking Radiometric Temperature Measurements of Plant Canopies," Applied Optics, 18 No. 13 (July 1980), pp. 2162-2168.

15. Schmugge, et al. "Survey of Methods." pp. 26-41.

16. For an analysis of the components of an atmospheric slant path absorption calculation, see David Anding, Band Model Methods for Computing Atmospheric Slant-Path Molecular Absorption, NAVSO P-2499-1 (Ann Arbor, Mich.: Willow Run Laboratories, Institute of Science and Technology (February 1967), 124 pp.

17. For a general discussion of the design of thermal infrared instrumentation and its integration on spacecraft, see the appropriate sections in Wolfe, ed. Handbook.

18. For a detailed discussion of infrared detectors, see R. K. Willarson and Albert C. Beer, eds. Semiconductors and Semimetals Volume 5 Infrared Detectors (NY: Academic Press Inc. 1970) 551 pp. D* curves as a function of wavelength for a number of different detectors can be found in Wolfe, ed. Handbook, pp. 471-500.

19. Barrett, Climatology, pp. 41-47.

20. Allison, et al., "Meteorological Satellites," pp. 10-11.

21. Ibid., pp. 20-22.

22. Ibid., pp. 8-9

23. Ibid., pp. 22-25.

24. NASA/GSFC, "HCMM Users Guide," p. 18.

25. Schmugge, et al., "Survey of Methods," J. Cihlar and A. K. McQuillan, "Applications of Satellite Thermal Infrared Measurements to Earth Resource Studies," Paper presented to the Remote Sensing Science and Technology Symposium, February 21-23, 1977, 35 pp.; and D. S. Kimes, et al., "Complexities."

26. W. D. Rosenthal, J. C. Harlan, and Bruce J. Blanchard, "Dryland Pasture and Crop Conditions as Seen by HCMM," (College Station, Tex.: Texas A&M University, January 1980) prepared for NASA/GSFC Contract No. NAS 5-24383 Progress Report 3712-9 for the period October 1979 - January 1980, 21 pp.

27. Paul Jeffrey Kocin, "Remote Sensing of Surface Moisture over a Watershed," M.S. Thesis, Department of Meteorology (University Park, Pa.: Pennsylvania State University, 1979), 62 pp.

28. Joint Research Center, Commission of the European Communities, ISPRA Establishment (Italy), HCMM Satellite Follow-On Investigation No. 025, "Soil Moisture and Heat Budget Evaluation on Selected European Zones of Agricultural and Environmental Interest," First Progress Report April 1 - August 31, 1979, 46 pp.

29. Brian J. L. Berry and Frank E. Horton, Urban Environmental Management Planning for Pollution Control, (Englewood Cliffs, N.J.: Prentice Hall, Inc., 1974), p. 39.

30. Helmut E. Landsberg, "City Air - Better or Worse," Symposium: Air Over Cities Tech Report A62-5 (Cincinnati, Ohio: U.S. Public Health Service, Taft Sanitary Engineering Center, 1961), pp. 1-22.

31. Joseph Kent Dodd, "Determination of Surface Characteristics and Energy Budget over an Urban Rural Area Using Satellite Data and a Boundary Layer Model," M.S. Thesis, Department of Meteorology, (University Park, Pa.: Pennsylvania State University, 1979), 87 pp.

32. P. M. Kuhn, L. P. Stearns, and R. O. Ramseier, "Airborne Infrared Imagery of Artic Sea Ice Thickness," NOAA Technical Report ERL 331-APCL 34, (Bounder, Colo.: United States Department of Commerce, 1975), 19 pp.

33. J. Cihlar and K. P. B. Thomson, "Diurnal Surface Temperature Variations and Their Usefulness in Mapping Sea Ice from Thermal Infrared Imagery," Presented at the Fourth Canadian Symposium on Remote Sensing, May 16 to 18, 1977, Quebec, Quebec; and Ambrose O. Poulin, "Significance of Surface Temperature in the Thermal Infrared Sensing of Sea and Lake Ice, "Journal of Sea and Lake Ice," Journal of Glaciology, 15, No. 73, 1975, pp. 277-283.

34. Ambrose O. Poulin, "On the Thermal Nature and Sensing of Snow Covered Artic Terrain," Research Note ETL-RN-73-4, (Fort Belvoir, Va.: U.S. Army Topographic Laboratories, May 1973), 173 pp.

35. R. J. Schertler, C. A. Raquet, and R. A. Svehla, "Applications of Thermal Imagery to the Development of a Great Lakes Ice Information System." In: H. S. Santeford, and J. L. Smith, eds. Advanced Concepts and Techniques in the Study of Snow and Ice Resources, (Washington, D.C.: National Academy of Sciences, 1973), pp. 513-522.

36. R. D. Seifert, R. F. Carlson, and D. L. Kane, "Operational Applications of NOAA - VHRR Imagery in Alaska," in A. Rango, ed. Operational Applications of Satellite Snowcover Observations, Proceedings of a Workshop held on August 18-20, 1975, Way Station, California, NASA SP-391 (Greenbelt, Md.: NASA/GSFC, 1975), pp. 143-155.

37. J. C. Barnes, C. J. Bowley, and J. L. Cogan, "Snow Mapping Applications of Thermal Infrared Data from the NOAA Satellite Very High Resolution Radiometer," Final Report under Contract No. 3-35385 (Concord, Mass.: Environmental Research & Technology, Inc., 1974).

38. V. R. Algazi and M. Suk, "An All Digital Approach to Snow Areal Mapping and Snow Modeling," in A..Rango, ed. Operational Applications. pp. 249-257.

39. James C. Barnes "Investigation of the Applications of HCMM Thermal Data to Snow Hydrology," ERT Document No. P-2061-10 HCMM 16 pp. Investigation No. 036 (Concord, Mass.: Environmental Research and Technology, Inc. April, 1980).

40. E. J. Pluhowski, "Urbanization and its Effect on Stream Temperature," Ph.D. Dissertation, (Baltimore, Md.: Johns Hopkins University, 1968), Department of Industry, January 1980. U.S. Geological Survey Prof. Pap. 627-D, (1970): 1-109.

41. R. T. Jaske and J. B. Goebel, Journal of the American Water Works Association 59, (1967), p. 935.

42. L. D. Jensen, R. M. Davies, A. S. Brooks, and C. D. Meyers, "The Effect of Elevated Temperature Upon Aquatic Invertebrates: A Review of the Literature Relating to Fresh Water and Marine Invertebrates," Johns Hopkins University, Department of Geography and Environmental Engineering, Baltimore, MD (1969).

43. Donald G. More and J. L. Heilman "Energy Budget Data as a Model Input for Assessing Regions of High Potential Ground Water Pollution." NASA Contract No. NAS 5-24206 (Brookings, S. Dak.: South Dakota State University, October-December 1979), 54 pp.

44. Gilbert Fielder and Duncan John Telfer, "Satellite Monitoring of Sea Surface Pollution," 2nd Progress Report No. 2-14/P6 for September 1, 1979 to December 31, 1979, Contract RD 1182/03 ID No. HCM-023 (London, U.K.: Department of Industry, January 1980), 27 pp.

45. C. S. Nilsson, J. C. Andrews, M. W. Lawrence, S. Bal , and A. R. Latham, "Heat Capacity Mapping Mission Project HCM-0151 Progress Report to April 30, 1980 Internal Tech. Memo 3/80." R.A.N. Research Laboratory, (Edge Cliff, N.W.W. Australia: Commonwealth of Australia, Department of Defense, 1980), 47 pp.

46. P. Y. Deschamps, R. Frouin, G. Cassanet and F. Verger "Sea Surface Temperature of the Coastal Zones of France," Laboratoire D'Optique Atmospherique Universite de Lille I and Laboratoire de Geographie Ecole Normale Superieure, December 1979, 50 pp.

47. J. Cihlar and A. K. McQuillan, "Applications," pp. 12-13 and 15-18.

48. Allison, et al., "Meteorological Satellites," pp 8-9 and p. 58, and D. Atlas, W. Bandeen, W. Shenk, J. Gatlin, and M. Maxwell, "Visions of the Future Operational Meteorological Satellite System." EASCON 1978 Electronics and Aerospace Systems Conference, Arlington, Va., September 25-27, 1978.

Table 1

U.S. Meteorological Satellite Programs

Name	Launched	Period (Min)	Perigee (km)	Apogee (km)	Inclination (Deg)	Remarks
TIROS I	01APR60	99.2	796	867	48.3	1 TV WA and 1 TV NA
TIROS II	23NOV60	98.3	717	837	48.5	1 TV WA 1 TV NA passive & active IR scan
TIROS III	12JUL61	100.4	854	937	47.8	2 TV WA HB IR IRP
TIROS IV	08FEB62	100.4	817	972	48.3	1 TV WA IR IRP HB
TIROS V	19JUN62	100.5	680	1119	58.1	1 TV WA 1 TV MA
TIROS VI	18SEP62	98.7	783	822	58.2	1 TV WA 1 TV MA
TIROS VII	19JUN63	97.4	713	743	58.2	2 TV WA IR ion probe HB
TIROS VIII	21DEC63	99.3	796	878	58.5	1st APT TV direct readout & 1 TV WA
Nimbus I	28AUG64	98.3	487	1106	98.6	3 AVCS 1 APT HRIR 3 axis stabilization
TIROS IX	22JAN65	119.2	806	2967	96.4	First wheel 2 TV WA global coverage
TIROS X	02JUL65	100.6	848	957	98.6	Sun synchronous 2 TV WA
ESSA 1	03FEB66	100.2	800	965	97.9	1st operational system 2 TV WA FPR
ESSA 2	28FEB66	113.3	1561	1639	101.0	2 APT global operational APT
Nimbus II	15MAY66	108.1	1248	1354	100.3	3 AVCS HRIR MRIR
ESSA 3	02OCT66	114.5	1593	1709	101.0	2 AVCS FPR
ATS I	06DEC66	24 hr	41,257	42,447	0.2	Spin scan camera
ESSA 4	26JAN67	113.4	1522	1656	102.0	2 APT
ESSA 5	20APR67	113.5	1356	1635	101.9	2 AVCS FPR
ATS III	05NOV67	24 hr	41,166	41,222	0.4	Color spin scan camera
ESSA 6	10NOV67	114.8	1622	1713	102.1	2 APT TV
ESSA 7	16AUG68	114.9	1646	1691	101.7	2 AVCS FPR S Band
ESSA 8	15DEC68	114.7	1822	1682	101.8	2 APT TV
ESSA 9	26FEB69	115.3	1637	1730	101.9	2 AVCS FPR S Band
Nimbus III	14APR69	107.3	1232	1302	101.1	SIRS A IRIS MRIR IDCS MUSE IRLS
ITOS 1	23JAN70	115.1	1648	1700	102.0	2 APT 2 AVCS 2 SR FPR 3 axis stabilization
Nimbus IV	15APR70	107.1	1200	1280	99.9	SIRS B IRIS SCR THIR BUV FWS IDCS IRLS MUSE
NOAA 1	11DEC70	114.8	1422	1472	102.0	2 APT 2 AVCS 2 SR FPR
NOAA 2	15OCT72	114.9	1451	1458	98.6	2 VHRR 2 VTPR 2 SR SPM
Nimbus 5	11DEC72	107.1	1093	1105	99.9	SCMR ITPR NEMS ESMR THIR
NOAA 3	06NOV73	116.1	1502	1512	101.9	2 VHRR 2 VTPR 2 SR SPM
SMS 1	17MAY74	1436.4	35,605	35,975	0.6	VISSR DCS WEFAX SEM
NOAA 4	15NOV74	101.6	1447	1461	114.9	2 VHRR 2 VTPR 2 SR SPM
SMS 2	06FEB75	1436.5	35,482	36,103	0.4	VISSR DCS WEFAX SEM
Nimbus 6	12JUN75	107.4	1101	1115	99.9	ERB ESMR HIRS LRIR TSDR SCAMS TWERLE PMR
GOES 1	16OCT75	1436.2	35,728	35,847	0.8	VISSR DCS WEFAX SEM
NOAA 5	29JUL76	116.2	1504	1518	102.1	2 VHRR 2 VTPR 2 SR SPM
GOES 2	16JUN77	1436.1	35,600	36,200	0.5	VISSR DCS WEFAX SEM
GOES 3	15JUN78	1436.1	35,600	36,200	0.5	VISSR DCS WEFAX SEM
TIROS N	13OCT78	98.92	849	864	102.3	AVHRR HIRS 2 SSU MSU HEPAD MEPED
Nimbus 7	24OCT78	99.28	943	955	104.09	LIMS SAMS SAM II SBUV TOMS ERB SMMR THIR CZCS
NOAA 6	27JUN79	101.26	807.5	823	98.74	AVHRR HIRS 2 SSU MSU HEPAD MEPED

APT	Automatic Picture Transmission TV	NEMS	Nimbus E Microwave Spectrometer
AVCS	Advanced Vidicon Camera System (1" Vidicon)	PMR	Pressure Modulated Radiometer
AVHRR	Advanced Very High Resolution Radiometer	SAM II	Stratospheric Aerosol Measurement II
BUV	Backscatter Ultraviolet Spectrometer	SAMS	Stratospheric and Mesospheric Sounder
CZCS	Coastal Zone Color Scanner	SBUV	Solar Backscatter Ultraviolet Spectrometer
DCS	Data Collection System	SCAMS	Scanning Microwave Spectrometer
ERB	Earth Radiation Budget	SCMR	Surface Composition Mapping Radiometer
ESMR	Electrically Scanned Microwave Radiometer	SCR	Selective Chopper Radiometer
FPR	Flat Plate Radiometer	SEM	Solar Environmental Monitor
FWS	Filter Wedge Spectrometer	SIRS	Satellite Infrared Spectrometer
HB	Heat Budget Instrument	SMMR	Scanning Multichannel Microwave Radiometer
HEPAD	High Energy Proton and Alpha Particle Detector	SPM	Solar Proton Monitor
HIRS	High Resolution Infrared Radiation Sounder	SR	Scanning Radiometer
HRIR	High Resolution Infrared Radiometer	SSU	Stratospheric Sounding Unit
IDCS	Image Dissector Camera System	TSDR	Tracking and Data Relay
IR	Infrared 5 Channel Scanner	THIR	Temperature Humidity Infrared Radiometer
IRIS	Infrared Interferometer Spectrometer	TOMS	Total Ozone Mapping Spectrometer
IRLS	Interrogation, Recording and Location Subsystem	TV	Television Cameras (1" Vidicon)
IRP	Infrared Probe		NA Narrow Angle = 12°
ITPR	Infrared Temperature Profile Radiometer		MA Medium Angle = 78°
LIMS	Limb Infrared Monitoring of the Stratosphere		WA Wide Angle = 104°
LRIR	Limb Radiance Infrared Radiometer	TWERLE	Tropical Wind Energy Conversion and Reference Level Experiment
MEPED	Medium Energy Proton and Electron Detector	VHRR	Very High Resolution Radiometer
MRIR	Medium Resolution Infrared Radiometer	VISSR	Visible Infrared Spin-Scan Radiometer
MSU	Microwave Scanner Unit	VTPR	Vertical Temperature Profile Radiometer
MUSE	Monitor of Ultraviolet Solar Energy	WEFAX	Weather Facsimile

TABLE 2

Thermal Infrared Research Programs from Aircraft

Research Facilities	Representative Publication
Coop. Effort: NASA-Ames; University of California-Davis; USDA-Arizona	Millard, J.P., Jackson, R.D., Goettelman, R.C., Reginato, R.J. and Idso, S.B. 1978, "Crop Water Stress Assessment Using an Airborne Thermal Scanner." Photo. Eng. and Remote Sensing, 44: 77-85.
University of South Dakota	Heilman, J.L. and D.G. Moore, 1980, "Thermography for Estimating Near-Surface Soil Moisture under Developing Crop Canopies." Jour. Appl. Meteorol., 19: 324-328.
University of Kansas	Heilman, J.L., E.T. Kanemausu, and N.J. Rosenberg, 1976, "Thermal Scanner Measurement of Canopy Temperatures to Estimate Evapotranspiration." Remote Sensing of Environment, 5: 137.
Texas A&M	Rosenthal, W.D., J.C. Harlen, B.J. Blanchard, and G. Coleman, 1979, "Pasture/Wheat Surface Temperature Differences - Indication of Soil Moisture Differences." Proceedings of 5th Symposium on Machine Processing of Remotely Sensed Data, LARS-Purdue University, pp. 224-233.
LARS-Purdue University	Kumar, R. and L. Silva, 1973, "Emission and Reflection from Healthy and Stressed Targets with Computer Analysis of Spectroradiometric and Multispectral Scanner Data." LARS Information Note 072473.
Environmental Research Institute of Michigan (ERIM)	Malila, W.A., 1972, "Radiation Balance Mapping with Multispectral Scanner Data." Remote Sensing of Earth Resources, Vol. 1, pp. 632-40. Ed. F. Shabroski, Tullahowa, Tennessee, University of Tennessee Space Institute.
Canadian Center for Remote Sensing (CCRS)	Cihlar, J., T. Sommerfeld and B. Paterson, 1979, "Soil Water Content Estimation in Fallow Fields from Airborne Thermal Scanner Measurements." Canadian Journal of Remote Sensing, 5: 18-32.
Netherlands Interdepartmental Working Community for Application of Remote Sensing Techniques (NIWARS)	Soer, G.J.R., 1980, "Estimation of Regional Evapotranspiration of Soil Moisture Conditions Using Remotely Sensed Crop Surface Temperatures." Remote Sensing of Environment, 9: 27-45.
CSIRO - Australia	Byrne, G.F., J.E. Begg, P.M. Fleming and F.X. Dunin, 1979, "Remotely Sensed Land Cover Temperature and Soil Water Status - A Brief Review." Remote Sensing of Environment 8: 291-305.

Bibliography

Allison, L. J.; Schmugge, T.; and Byrne, G. "A Hydrological Analysis of East Australian Floods Using Nimbus-5 Electrically Scanning Radiometer Data." Bulletin of the American Meteorological Society 60, No. 12 (Dec. 1979): 1414-1427.

Allison, L. T., ed.; Schnapf, A.; Dieson, B. C., III; Martin, P. S.; Schwalf, A. and Bandeen, W. "Meteorological Satellites." NASA Technical Memorandum 80704. Greenbelt, Md.: Goddard Space Flight Center (June 1980): 71 pp.

Anding, David. Band-Model Methods for Computing Atmospheric Slant-Path Molecular Absorption. NAVSO P-2499-1. Ann Arbor, Mich.: Willow Run Laboratories, Institute of Science & Tech. (Feb. 1967).

Atlas, D.; Bandeen, W.; Shenk, W.; Gatlin, J.; and Maxwell, M. Visions of the Future Operational Meteorological Satellite System. EASCON 1978 Electronics and Aerospace Systems Conf. Arlington, Va., (Sept. 25-27, 1978).

Barnes, James C. "Investigation of the Application of HCMM Thermal Data to Snow Hydrology." ERT Document No. P-2061-10 HCMM. Investigation No. 035. Concord, Mass.: Environmental Res. and Tech., Inc. (April 1980), 16 pp.

Barnes, James C.; Bowley, C. G.; and Cogen, J. L. "Snow Mapping Applications of Thermal Infrared Data from the NOAA Satellite Very High Resolution Radiometer." Final Report under Contract No. 3-35385. Concord, Mass.: Environmental Research and Technology, Inc., 1974.

Barrett, E. C. Climatology from Satellites. London: Methuen and Co. Ltd., 1974.

Barry, R. G. and Chorley, R. J. Atmosphere, Weather and Climate. 2nd Ed. London: Methuen and Co., Lts., 1971.

Berry, Brian J. L. and Horton, Frank E. Urban Environmental Management Planning for Pollution Control. Englewood Cliffs, N.J.: Prentice Hall, Inc., 1974.

Chapman, John D. and Sherman, J. C., ed. Oxford Regional Economic Atlas of the United States and Canada. 2nd Ed. London: Oxford University Press, 1975.

Cihlar, J. and McQuillan, A. K. "Applications of Satellite Thermal Infrared Measurements to Earth Resources Studies." Paper presented at the Remote Sensing Science and Technology Symposium. (February 21-23, 1977), 35 pp.

Cihlar, J. and Thomson, K. P. B. "Diurnal Surface Temperature Variations and Their Usefulness in Mapping Sea Ice from Thermal Infrared Imagery." Paper presented at the Fourth Canadian Symposium on Remote Sensing. Quebec, Quebec (May 16-18, 1977).

Deschamps, P. Y.; Frouin, R.; Cassanet, G; and Verger, F. "Sea Surface Temperature of the Coastal Zones of France." Laboratoire D'Optique Atmospherique, Universite de Lille I and Laboratoire de Geographie Ecole Normale Superieure (December 1979), 50 pp.

Dodd, Joseph Kent. "Determination of Surface Characteristics and Energy Budget Over an Urban Rural Area Using Satellite Data and a Boundary Layer Model." M.S. Thesis, Pennsylvania State University, 1979.

Engineering Summer Conferences. Fundamentals of Infrared Technology No. 78/6909. Ann Arbor, Mich.: University of Michigan (June 2-6, 1969).

Engineering Summer Conferences. Advanced Infrared Technology No. 95/6910. Ann Arbor, Mich.: University of Michigan (June 9-13, 1969).

Engineering Summer Conferences. Infrared Radiometry - Instrument Calibration and Precision Measurements No. 21/6911. Ann Arbor, Mich.: University of Michigan (June 16-20, 1969).

Fielder, Gilbert and Telfer, Duncan John. "Satellite Monitoring of Sea Surface Pollution." London: U.K., Department of Industry, 2nd Progress Report No. 2-14/P6 for Sept. 1, 1979 to Dec. 31, 1979 Contract RD 1182/03, ID Number HCM-023 (January 1980): 27 pp.

Geiger, R. The Climate Near The Ground. trans. ed. Cambridge. Harvard University Press, 1959.

Heilman, Quentin A. and Nuesch, Daniel R. "Selection of a Seventh Spectral Band for the Landsat-D Thematic Mapper." NASA CR-ERIM 130100-4-F, Ann Arbor, Mich.: Environmental Research Institute of Michigan Contract No. NAS 9-15352. (January 1978), 94 pp.

Holtz, Robert K. ed. The Surveillant Science Remote Sensing of the Environment. Boston: Houghton Miflin, 1973.

Jaske, R. T. and Goebel, J. B. Journal of the American Water Works Association. 59 (1967).

Jensen, L. D.,; Davies, R. M.; Brooks, A. S.; and Meyers, C. D. "The Effect of Elevated Temperature Upon Aquatic Invertebrates: A Review of the Literature Relating to Fresh Water and Marine Invertebrates." Baltimore Md.: Johns Hopkins University, Department of Geography and Environmental Engineering, 1969.

Joint Research Center. Commission of the European Communities ISPRA Establishment (Italy) HCMM Satellite Follow-On Investigation No. 025. "Soil Moisture and Heat Budget Evaluation in Selected European Zones of Agricultural and Environmental Interest." First Progress Report (April 1 - August 31, 1979): 46 pp.

Kimes, D. S.; Idso, S. B.; Pinter, P. J. Jr.; Jackson, R. D.; Reginato, R. J. "Complexities of Nadir-Looking Radiometric Temperature Measurements of Plant Canopies." Applied Optics. 19 No. 13/1 July 1980 pp. 2162-2168.

Kocin, Paul Jeffery. "Remote Sensing of Surface Moisture Over a Watershed." M.S. Thesis, Pennsylvania State University, 1979.

Kuhn, P. M.; Stearns, L. P.; and Ramseier, R. O. "Airborne Infrared Imagery of Artic Sea Ice Thickness." NOAA Technical Report ERL 331-APCL 34. Boulder, Colo.: United States Department of Commerce (1975): 19 pp.

Kunde, V. G. "Theoretical Relationships Between Equivalent Blackbody Temperatures and Surface Temperatures Measured by the Nimbus HRIR Radiometer." NASA SP-89. Greenbelt, MD. National Aeronautics and Space Administration/Goddard Space Flight Center, 1965.

Landsberg, Helmut E. "City Air - Better or Worse." Symposium Air Over Cities Technical Report A62-5 Cincinnati, Ohio: United States Public Health Service, Taft Sanitary Engineering Center, 1961.

Legualt, R. R. "Discrimination Introduction." Notes in the University of Michigan Engineering Summer Conferences. Advanced Infrared Technology: An Intensive Short Course. University of Michigan No. 95/6910. Ann Arbor, Mich.: University of Michigan (June 9-13, 1969).

Lillisand, T. M. and Kiefer, R. W. Remote Sensing and Image Interpretation. New York: John Wiley & Sons, 1979.

MacDonald, R. B.; Bauer, M. E.; Allen, R. D.; Clifton, J. W.; Erickson, J. D.; and Landgrebe, D. A. "Results of 1971 Corn Blight Watch Experiment." Proceedings of the Eighth International Conference on the Remote Sensing of the Environment. Ann Arbor, Mich.: ERIM (October 2-6, 1971): 157-190.

More, Donald G. and Heilman, J. L. "Energy Budget Data as a Model Input for Assessing Regions of High Potential Ground Water Pollution." 2nd Progress Report No. 2-14/P6 for Sept. 1, 1979 - Dec. 31, 1979. Contract RD 1182/03. ID No. HCM-023. Longon: U.K., Department of Industry (Jan. 1980): 27 pp.

Munn, R. E. Descriptive Micrometeorology. New York, NY: Academic Press, 1966.

National Aeronautics & Space Administration/Goddard Space Flight Center. "Heat Capacity Mapping Mission (HCMM) Data Users Handbook for Applications Explorer Mission-A (AEM)." (December 1978).

Nilsson, C. S.; Andrews, J. C.; Lawrence, M. W.; Ball, S.; and Latham, A. R. "Heat Capacity Mapping Mission Project HCM-0151 Progress Report to 30 April 1980 Interna. Tech. Memo 3/80." Edge Cliff, N.S.W. Australia, R.A.N. Research Laboratory Commonwealth of Australia Department of Defense (1980), 47 pp.

Oort, Abraham H. "The Energy Cycle of the Earth." Scientific American 223 No. 3. (Sept. 1970): 54-63.

Pluhowski, E. J. "Urbanization and Its Effects on Stream Temperature." Ph.D. Dissertation, Johns Hopkins University, 1968.

________. United States Geological Survey Prof. Paper 627-D (1970): 1-109.

Poulin, Ambrose O. "On the Thermal Nature and Sensing of Snow Covered Artic Terrain." Fort Belvoir, Va: U.S. Army Engineer Topographic Laboratories Research Note ETL-RN-73-4. (May 1973), 173 pp.

Poulin, Ambrose O. "Significance of Surface Temperature in the Thermal Infrared Sensing of Sea and Lake Ice." Journal of Glaciology 15, No. 73, (1973).

Price, John C. "Thermal Inertia Mapping: A New View of the Earth." Journal of Geophysical Research 82, No. 18 (June 20, 1977): 2582-2590.

Rango, A., ed. Operational Applications of Satellite Snowcover Observations. Proceeding of a Workshop held Aug. 18-20, 1975, Way Station, Calif., NASA SP-391 Greenbelt, MD.: National Aeronautics and Space Administration/ Goddard Space Flight Center, 1975.

Rosenthal, W. D.; Harlan, J. C.; Blanchard, Bruce J. "Dryland Pasture and Crop Conditions as Seen by HCMM." College Station, Texas: Texas A&M U, Prepared for NASA GSFC Contract No. NAS 5-24383 Progress Report 3712-9 for period October 1979 - January 1980: 21 pp.

Sabins, Floyd F. Jr. Remote Sensing Principles and Interpretation San Francisco: W. H. Freeman & Co. 1978.

Santeford, H. W. and Smith, J. L., ed. Advanced Concepts and Techniques in the Study of Snow and Ice Resources. Washington, D.C.: National Academy of Sciences, 1973.

Schmugge, T. J.; Jackson, T. J.; and McKim, H. L. "Survey of Methods for Soil Moisture Determination." NASA Technical Memorandum 80587. Greenbelt, Md.: NASA/Goddard Space Flight Center (November 1979), 74 pp.

United Nations. World Meteorological Organization. "The Role of Meteorological Satellites in the World Weather Watch." World Weather Watch Planning Report No. 18. Geneva: World Meteorological Organization (1967): 38 pp.

Willardson, R. K. and Beer, Albert D., ed. Semiconductors and Semimetals. Vol. 5: Infrared Detectors. New York, NY: Academic Press, 1970.

Wolff, Edward A. and Mercanti, Enrico P. ed. Geoscience Instrumentation. New York, NY: John Wiley & Sons, Inc., 1974.

Wolfe, William L. Handbook of Military Infrared Technology. Washington, DC: Department of Navy, Office of Naval Research 1965.

Woodwell, George M. "The Energy Cycle of the Biosphere." Scientific American 223; No. 3 (Sept. 1970): 64-74.

Woodwell, George M. "Primary Production in Terrestrial Ecosystems." American Zoologist 8, No. 1 (February 1968): 16-30.