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Day and night cloud patterns, atmospheric structure, and global heat balance have received intensive study in—

Research with Tiros radiation measurements

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The advantages of viewing the earth and its atmosphere from an orbiting meteorological satellite have been thoroughly expounded by now and are well known. The Tiros series has demonstrated the usefulness to the meteorologist of observations of large-scale cloud cover and similar features with television cameras. TV observations, while providing a maximum resolution of the areas viewed, nevertheless have two distinct disadvantages: Their response is limited to a rather small portion of the visible spectrum (0.5–0.7 microns) and the absolute intensities of the radiation received by the camera cannot be measured. The greatest asset of TV observations therefore lies in the ability of the cameras to map meteorological features with relatively high resolution.

Much more can be learned, however, about the physical structure of the atmosphere and its meteorological implications by extending observations to other portions of the spectrum, particularly to the infrared, and by obtaining a more precise measurement of intensities of radiation emanating from various regions of the globe. This makes it highly desirable to supplement TV photographs with radiometric observations.

A radiometer generally consists of a photodetector (the nature of which will largely depend on the desired spectral response), an optical filter and, possibly, light gathering lenses or mirrors. It has to be well calibrated in terms of its irradiance, but a variety of spectral regions may be chosen by selecting the proper components, such as transmission filters, reflective coating, etc. All measurements discussed here resulted from rather simple instruments which reflect the state of satellite radiometry of several years ago, when the idea of this type of experiment was first realized.

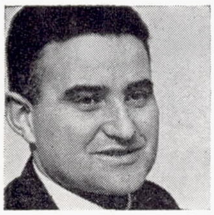
Today, one might conceive of considerably more advanced, high-resolution radiometric sensors, some operating in the extremes of the electromagnetic spectrum such as microwave radiometers, but their concepts are described elsewhere in this issue (see page 85). To some extent, the design of such future devices will undoubtedly be based on the results reported here.

Radiometric experiments have been generally performed by meteorological satellites for one or a combination of the following three reasons:

1. To map the distribution of cloud patterns both day and night and determine heights of cloud tops. The simplest device to accomplish this is a radiometer operating in a narrow portion of the infrared spectrum where the transmission through clear atmosphere is a maximum (that is, an atmospheric "window"). One of the most effective windows for this purpose lies in the 10–11 micron region. The radiation received at the instrument is assumed to be a known function of the effective temperature only of the emitting surface (ground or cloud top). Since temperature distribution with height in the troposphere is assumed to be known from balloon or climatological data, radiation measurements can not only detect the presence or absence of clouds, but also determine the heights of the cloud tops. Two requirements must be fulfilled by the radiometer: The field of view of the instrument must be reasonably small to provide sufficiently high spectral resolution (0.5 and 3.0 deg are used in present high- and medium-resolution instruments), and the field of view must scan the earth continuously to give adequate coverage.

2. To determine the structure of the atmosphere. Here again, the radiometer must operate within a narrow spectral region near the center of a strong absorption band of one of the atmospheric constituents (6.7 microns for H_2O or 15 microns for CO_2). The radiation received is a function of both the temperature and the concentration of the constituent with height. By measuring radiation in the absorption band and comparing it with measurements in a window channel, the temperature structure of the lower atmosphere can be derived if the concentration of the absorbing gas is known (as in the case of CO_2), or the total content of the absorber in the viewed column can be determined if the temperature structure is known. Total amounts of water vapor in the column may be determined by this last method. Because of the high spectral resolution necessary, it has not been possible so far to use the former method. Such an instrument is now under development (see page 85).

3. To determine the balance be-



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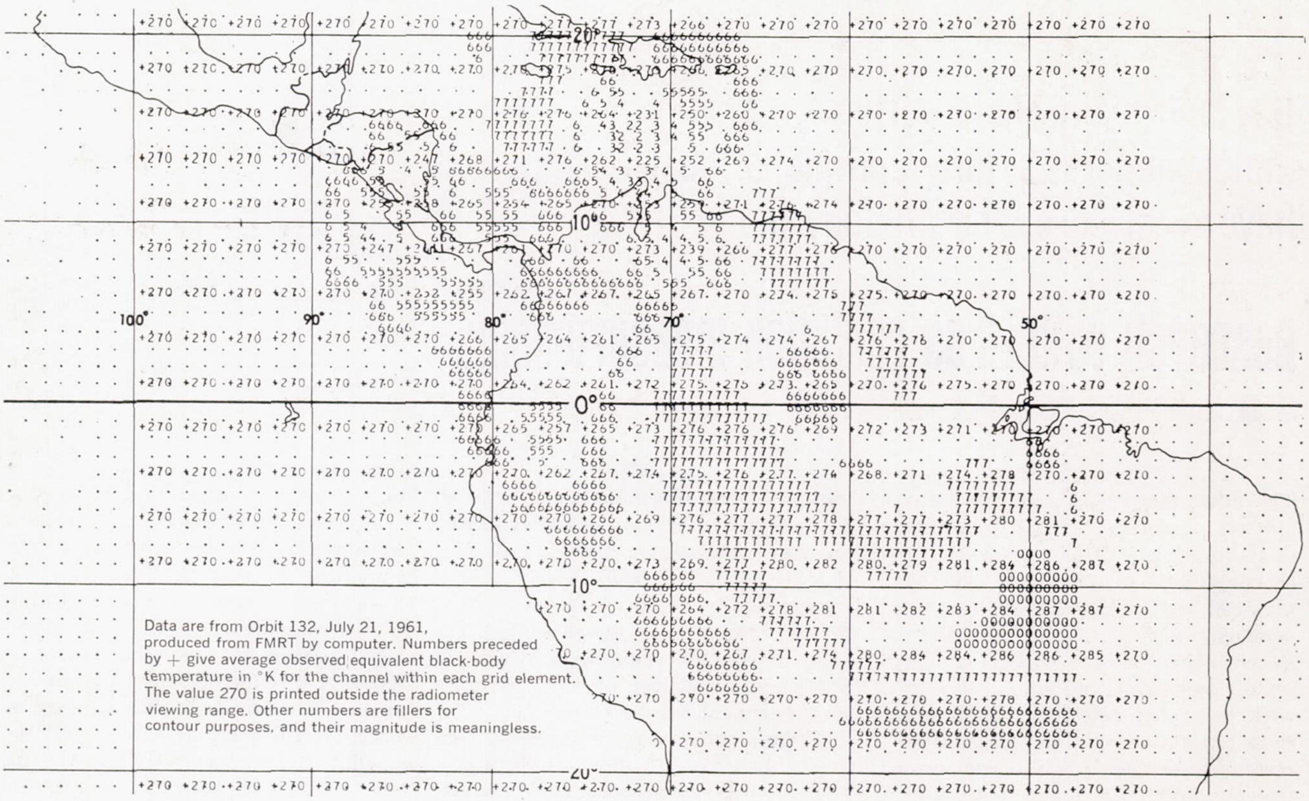
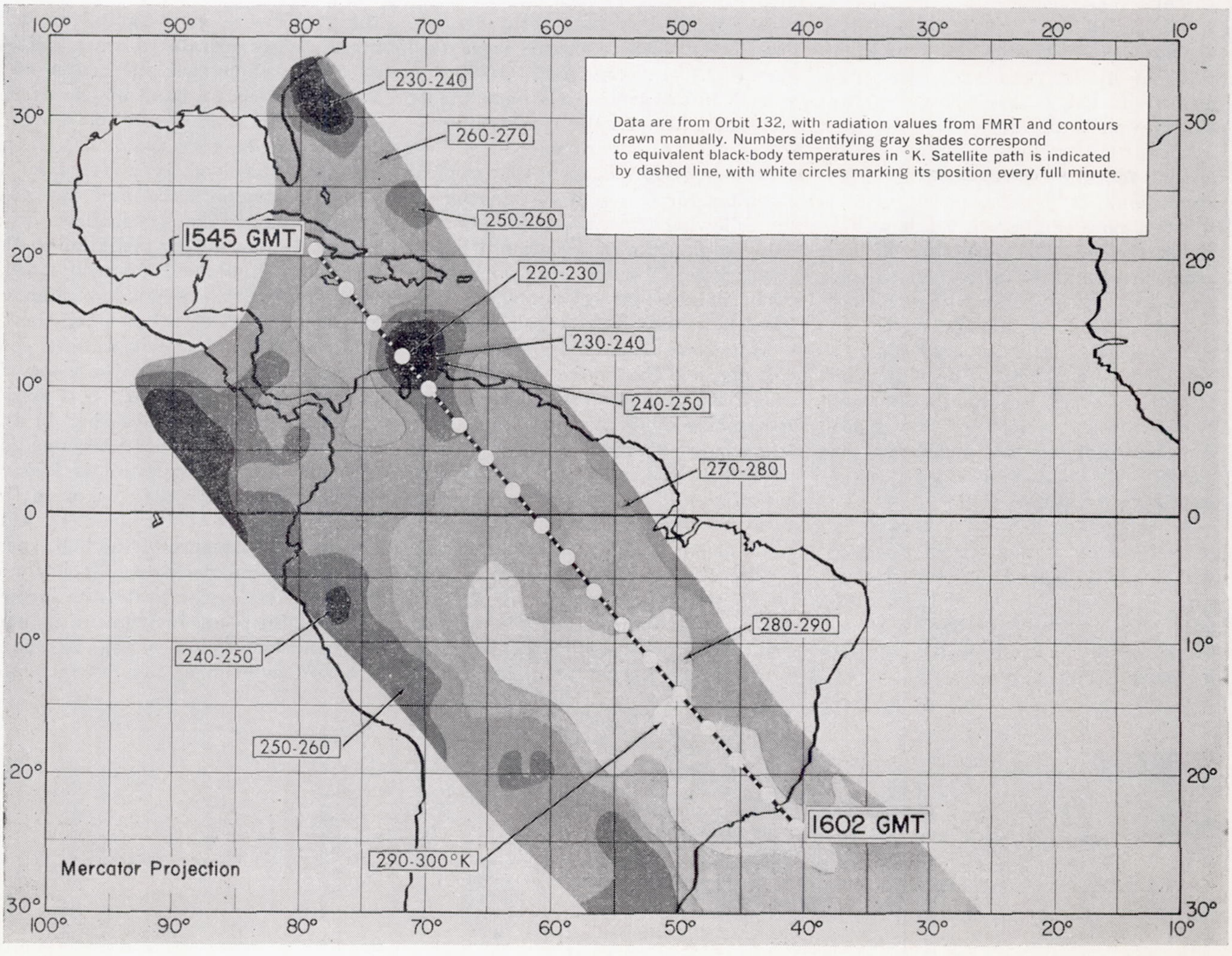
TIROS III RADIATION MAPS, 8–12 MICRON CHANNEL—top, produced by computer; bottom, reduced manually.





tween solar energy absorbed and thermal energy emitted by the earth and the atmosphere. This balance is a major factor in determining the energy stored in the atmosphere and available to be transformed into dynamic processes. Measurements for this purpose may be performed by two extremely simple sensors. One must operate in the solar spectrum (0.2–4 microns) to detect reflected solar energy from the earth, and the other in the infrared (5–30 microns) to receive emitted thermal radiation. Spatial resolution in this case is not of the essence, and the field of view may be one order of magnitude larger than for a medium-resolution scanning radiometer.

Each of these three areas holds great importance for meteorology. A complete mapping of cloud distribution and heights is of immense importance to the synoptic meteorologist: a knowledge of global height distributions of temperature and water vapor could eventually find its way into schemes for numerical weather forecasting, and the measurement of radiative energy balance might provide a powerful tool to explore the formation of storm systems.

Of the three areas, the first has been most extensively satisfied by measurements from all meteorological satellites in the past[1–3] and will also be strongly pursued in the near-future with Nimbus experiments.[4] Measurements from Tiros[5–8] and Explorer VII have been highly encouraging with respect to measurement of total energy fluxes, and some results were obtained from Tiros III and IV water vapor in the atmosphere.[9]

In addition, these experiments have produced a wealth of secondary results, such as background information for the better use of horizon scanners,[10] the durability of optical components in the space environments,[11] the development of useful infrared calibration techniques in the laboratory,[12] and the development and use of a magnetic attitude-control device.[13] The experiments and their basic results are reviewed below.

Experiments to Date. The first meteorological satellite, Vanguard II, carried as its only payload two PbS photocells with appropriate optical systems, electronics, tape recorder, and telemetering. The photocells were to scan the earth to map cloud cover. The scanning motion was to be produced by the regular spin of the satellite.[14] Unfortunately, the satellite tumbled and no systematic maps could be generated. However, the experiment was successful inasmuch as it demonstrated the capability of this technique and paved the way for the subsequently successful Tiros radiation experiments.

The sensors flown in Tiros II, III, and IV have been fully described elsewhere.[15] Each satellite contains two instruments. One is a nonscanning radiometer with broad response in both the visible and infrared regions and a rather low spatial resolution. Its field of view is approximately 55 deg. The other is a scanning radiometer which scans as the satellite spins. It is of medium spatial resolution, has a 5-deg field of view, and responds to radiation in five different spectral regions determined by optical filters. Three of these regions are in the infrared between 5.9 and 6.7 microns, 8 and 12 microns, and 8 and 30 microns. The other two lie mainly in the visible portion of the spectrum between 0.50 and 0.75 microns and 0.2 and 7.0 microns. These spectral regions are purely nominal since the response of the instrument within these regions is far from uniform. Therefore, the exact spectral response curves must be used when the energy distribution in each channel is calculated. Typical curves for Tiros III have been given elsewhere.[16]

In the 5.9 to 6.7 micron channel, a maximum of absorption due to water vapor is encountered. Energy in this channel is therefore received mainly from the highest altitudes where water vapor may be found in the atmosphere. In contrast, the optical depth is a maximum in the 7.5 to 13.5 channel, since absorption due to any of the atmospheric constituents—except ozone, which covers only a minor portion of this channel—is very small. The 7.0 to 32.0 channel covers almost 80% of the total black-body energy emitted by the earth, while the total solar energy reflected from the earth is contained in the 0.20 to 7.0 channel. The 0.50 to 0.75 channel is of interest because it covers only a narrow spectral region very near the maximum of solar-energy distribution, and is similar in its spectral response to the TV cameras carried on the same satellite.

One of the basic differences between the wide-field and five-channel instruments is that the five-channel radiometer scans the earth during all portions of the orbit, while the wide-field radiometer fully views the earth during less than 1/5 of the orbit. The wide-field instrument measures the radiant emittance of a target by means of a thermistor whose resistance is a function of the absorbed energy flux. This is accomplished over the whole spectrum with two detectors: a black one equally sensitive to radiation emitted and reflected from the earth, and a white one predominantly sensitive to emitted radiation. The portion of solar energy reflected from the earth (the earth's albedo) and the apparent black-body temperature for earth can be determined by comparing the energies received by the black and white detectors. A complete description of this instrument has been given by Hanel.[17]

Very much in contrast to the wide-field radiometer, the sensors in the five-channel instrument are alternately, and in rapid succession, illuminated with two diametrically opposed fields of view, one scanning the earth and the other pointing into outer space. The sensors therefore measure the difference of the energy fluxes in the two directions. Since the flux from outer space is essentially zero, this serves as a reliable reference.

A detailed description of this instrument and its scanning mechanism is contained in.[15] Further instrumental details, such as recording, transmitting, and electrical conversion of the measurements have been described.[18]

In addition, Tiros III and IV each carried radiation sensors of the type used in Explorer VII and described below.[21]

On Explorer VII, incident radiation from the sun, reflected solar radiation from the earth, and emitted radiation from the earth are measured with simple bolometers in the form of hollow silver hemispheres. The hemispheres are thermally isolated from, but in close proximity to, specially aluminized mirrors. The image of the hemisphere which appears in the mirror makes the sensor look like a full sphere. The mirror is made large enough so that no part of the hemisphere bolometer "sees" the satelite itself. The temperatures of the thin silver hemispherical bolometers are measured by glass-coated bead thermistors, mounted so as to provide good thermal contact to the hemisphere. In addition, provision is made to measure the temperature of the mirrors.[21]

It is possible to show that a mirror-backed hemisphere by virtue of the satellite spin acts, as far as the radiation fluxes are concerned, very similar to an isolated sphere in space. Two hemispheres are coated black, which makes them respond about equally to solar and terrestrial radiation. Another hemisphere, coated white, is more sensitive to terrestrial radiation than to solar radiation. A fourth, with a gold surface, is also more sensitive to solar radiation. A black sphere, mounted on the axis of the satellite at the top, is used to determine any deterioration in the mirror surfaces by comparison with the blackened hemispheres. Finally, a small Tabor-surfaced hemisphere equipped with a shade to protect it from direct sunlight can be used to measure reflected sunlight when the axis of the satellite points to the earth's surface.

The information telemetered to the earth's surface is sensor *temperatures.* The radiation fluxes are obtained by using these temperatures in heat-balance equations.

Two scanning radiometers similar in concept to the Tiros experiments will be flown in Nimbus. The radiometers have now reached the prototype stage. One, a high resolution radiometer with a 1/2-deg field of view, will map thermal radiation in an atmospheric window between 3.5 and 4.2 microns.

The other, a medium-resolution radiometer, is a continuation of the Tiros five-channel radiation experiment. Early versions will have about the same wavelength ranges as the Tiros radiometer but will be improved. The spectral range of the 8–12 micron channel will be narrowed to a 1-micron band from approximately 10 to 11 microns, where the window is most transparent. Spectral response of other channels has also been improved.

The major advance, however, is in the check of calibration during operation in space. Both medium- and high-resolution radiometers will scan the radiometer structure, which has been converted into a black body by deep grooves and a proper coating, and which has a separate telemetering channel to monitor its temperature. Now two points on the calibration curve are available for all thermal (infrared) channels—zero (outer space) and a point close to the maximum of the dynamic range. However, some channels which are insensitive to infrared, such as the 0.25- to 4-micron channel of the medium-resolution radiometer, need other means of checking the calibration. Here the sun provides the calibration signal.

Twice each orbit, the lower surface of Nimbus is exposed to sunlight, just before and just after the spacecraft enters and leaves the earth's penumbra. A metal reflector and a sapphire bead then channel sunlight into the view of the radiometer.

In contrast to Tiros, where scanning motion is provided by satellite spin, Nimbus radiometers generate the scan internally, by a rotating mirror. Scan lines are perpendicular to the velocity vector of the satellite and provide complete coverage of the earth from horizon to horizon without overlaps or gaps in the scan pattern at the subsatellite point. Use of the atmospheric window from 3.5 to 4.2 microns made the application of fast semiconductive detectors possible without going to excessive cooling requirements. In the satellite, a radiative cooling system maintains a detector temperature of approximately —80 C, sufficient for the lead selenide detector cell used in the high-resolution radiometer. The cooler is a surface of high emissivity, 2 1/2 by 4 cm in size. It is thermally in contact with the cell but isolated from the spacecraft, exposed to outer space but never to the sun. This is possible on Nimbus since the orientation of the spacecraft is actively controlled with respect to earth and sun.

Aside from engineering the instruments, there are two major challenges common to all radiometric experiments: Calibration of the sensors and handling the vast amounts of information continually accumulated by the satellite. These challenges are particularly pronounced in the Tiros five-channel radiometer experiment, where each channel must not only be calibrated in terms of its total irradiance but the precise spectral response must also be known since in one orbit the instrument feeds over one million data bits to a digital computer.

The calibration for total irradiance is accomplished with specially constructed black bodies in vacuum for the thermal channels and with precision calibrated tungsten sources for the solar-radiation channels. Calibration for spectral irradiance becomes a major difficulty in the long wave end of the 8–30 micron channel. In the visible channels, this calibration must be performed with great precision because the tungsten calibration target and the reflecting earth have vastly different radiative temperatures (2800 and 6000 K).

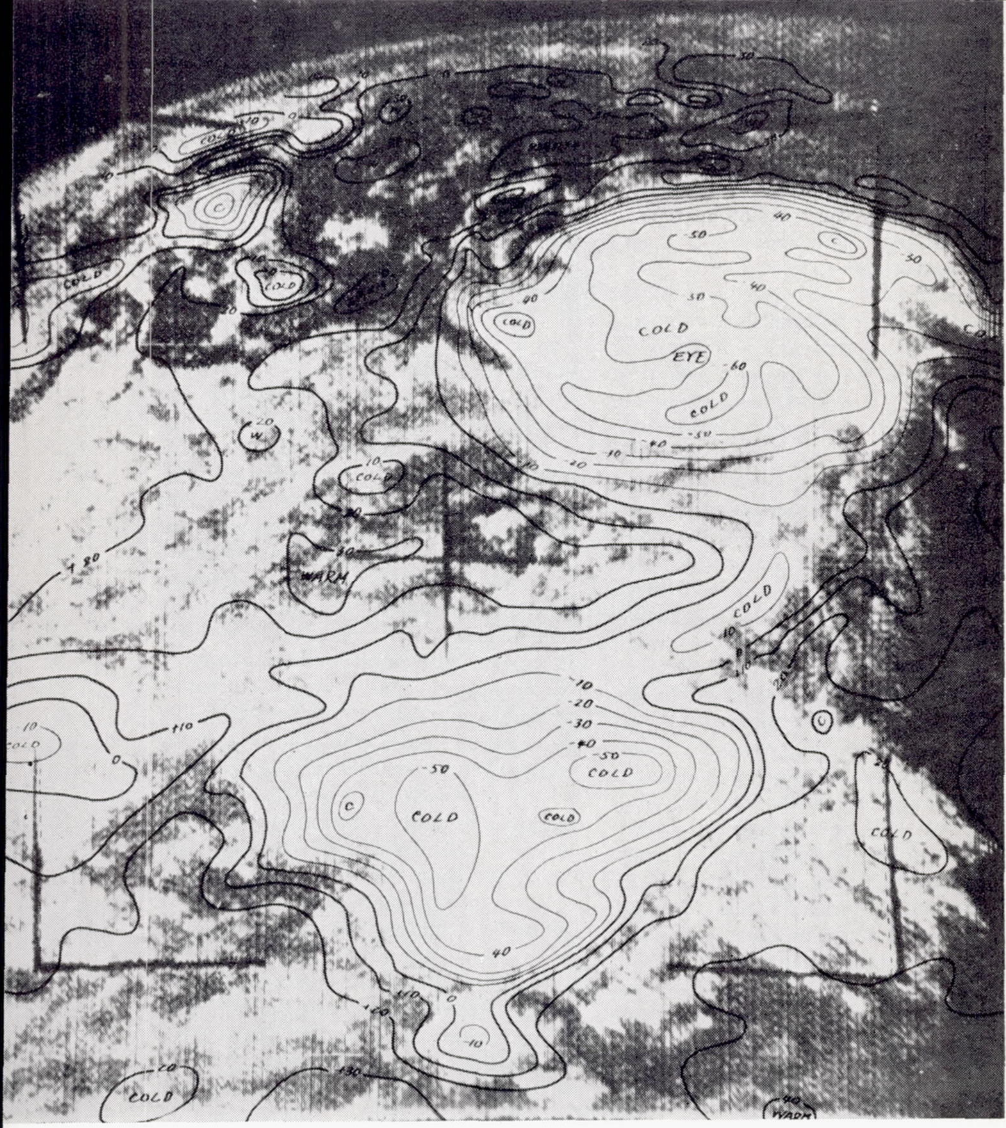
Data are recorded on a magnetic tape containing the radiation intensities in digital form as a function of geographic location, viewing geometry and time. This record, called FMRT (Final Meteorological Radiation Tape), is produced by a highly complex program in an IBM 7090 computer from digitized telemetry records and a knowledge of the calibration of the sensors and the satellite's location and attitude. The latter is especially cumbercome to incorporate since none of the satellites flown so far has been earth-oriented. In utilizing the data that is, in plotting cloud cover maps, deriving energy budgets, or performing other research on radiation data, it is most advantageous to program the problem and operate directly on the FMR tape without intermediate printouts.

For those who do not have easy access to large digital computers data catalogs were published on Tiros II[19] and III[20] which contain a representative sample of data collected, and are intended to show the potential of the radiation measurements. The map on page 77 is a typical example of such a data display. Its significance will be discussed below.

Review of Experimental Results. The wide-field radiometers on Explorer VII[3] have already given an indication that patterns of emitted radiation fluxes from the earth can be well correlated with cloud patterns. It was the Tiros five-channel instrument, with its much greater resolution, however, which demonstrated most convincingly its ability to map cloud cover. To date, innumerable cases have been analyzed where radiation in the 8–12 micron window channel was compared with cloud photographs and other synoptic data and the agreement was found to be excellent.

A typical example is depicted in the illustrations on page 77. The map shown in the top illustration was drawn automatically by the computer directly from the FMR tape, and is typical for the results presented in the Radiation Data Catalogs.[19,20] In the other illustration, the same map has been contoured manually for better clarity, with regions of different black-body temperature ranges shown in different shades of grey, and the path of the satellite subpoint from northwest to southeast also indicated. The region of minimum temperature (200–230 K) near 13° N, 72° W indicates a circular cloud system which, because of its very low temperature, must extend to extreme altitudes. Indeed, this system coincides with hurricane Anna, identified through cloud photographs and aircraft reconnaissance. In a series of similar radiation maps, the storm can be tracked over its entire path almost 4000 km.

Because of the small scale of plotting, the temperatures shown on the maps generally represent averages over several scan spots within one grid element. Therefore the maps do not necessarily show the true minimum temperature measured in the storm center. In fact, careful examination of each scan spot reveals that this temperature ranged between 200 and 210 K. From a climatological temperature profile, shown on page 80, one finds the height of the cloud top for the hurricane at approximately 15 km, while the cloud system just to the southeast of the storm shows minimum temperatures near 230 K and therefore a cloud top height of approximately 11 to 12 km.

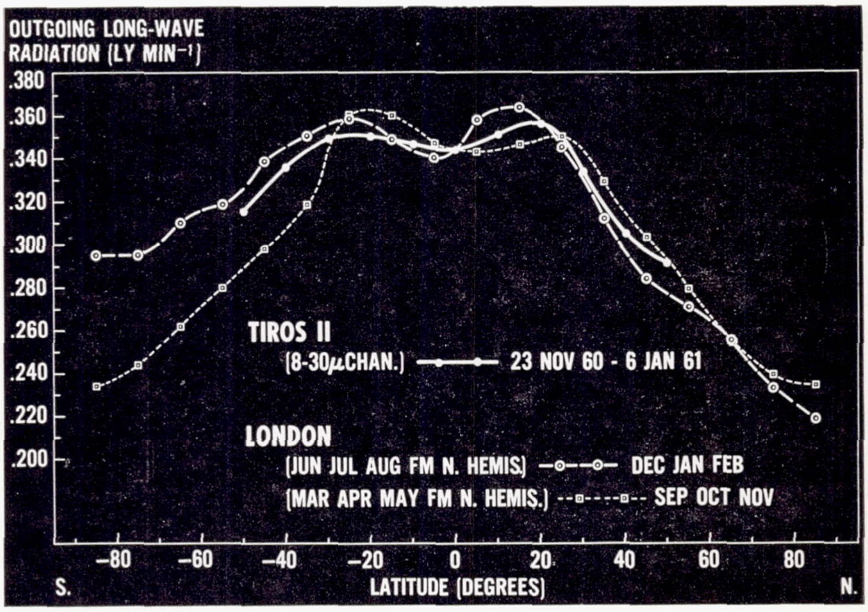


Such height determinations can only be made from radiometer data and are not at all evident from cloud photographs such as the one shown at left here. The illustration shows a Tiros photograph over hurricane Anna taken at the time of the radiation measurements of the two illustrations on page 77. In addition, manually reduced contour lines of radiation values in the 8–12 micron channel prepared from the *analog* telemetering records are superimposed on the photograph. The analysis of these analog radiation data and the contouring of the photograph shown adjacent was carried out by Prof. T. Fujita and his staff at the Univ. of Chicago. His kind permission to reproduce his results in this article is gratefully acknowledged.

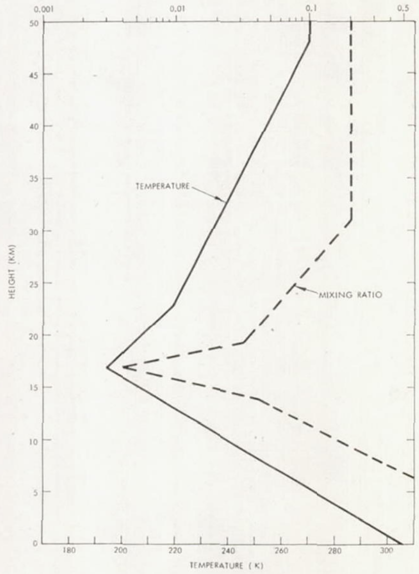
The perfect match between radiation and cloud patterns is striking. It is this type of presentation, given on an incomparably larger scale than in the two maps, which demonstrates the full cloud-mapping ability of the radiation sensors. Unfortunately, in the illustration at the left, the radiation intensities were plotted on a relative scale only and the contour numbers shown are arbitrary and not well suited for cloud height determinations.

Additional features apparent in the map on page 77 are the huge clear area (290–300 K) over central South America corresponding to the high-pressure system one would expect to find in this subtropical belt in the winter hemisphere, and the large cloud mass off the coast of Florida. Comparisons such as the one shown in the

Hurricane Anna as seen by Tiros III (Orbit 132) near 13° N, 72° W. Contour lines represent relative radiation intensities from 8–12 micron channel. Radiation contours drawn from raw analog data.



Outgoing Long-wave Radiation vs. latitude, measured and predicted. Tiros II results (solid curve) are compared with theoretical curves of J. London (dashed curves).



Temperature and Water Vapor Mixing Ratio vs. height. Temperatures taken from data on tropical atmosphere. Water-vapor profile fits radiation data over Hurricane Anna.

map on page 80 and the ability of computers to create meaningful maps from the digitized data clearly demonstrate that radiometric observations in an infrared "window" region may well be used for synoptic analysis in future real-time meteorological satellite systems.

It must be strongly emphasized, however, that such systems are still very much in the future. The example given for the determination of cloud-top heights illustrates the principle only and any cloud height measurement with present Tiros instruments is very approximate. Many difficulties of a theoretical nature must still be overcome. For example, no true atmospheric window really exists where the transmission even in clear atmosphere is 100%. Black-body temperature measurements in the 8–12 micron channel by Tiros must therefore be corrected for absorption by water vapor, carbon dioxide, and ozone. A theory to apply such corrections was developed by Wark and Yamamoto.[2] Even after applying these corrections, investigations show that, especially when cloud tops are near the earth's surface, radiation measurements yield temperatures 5–10 K too low.

There could be several reasons to explain this: Clouds which were assumed to radiate as black bodies in this region of the spectrum may have an emissivity considerably less than 1; particles in the atmosphere such as aerosols or thin cirrus clouds, not visible in TV photos, may produce additional absorption not accounted for in the Wark-Yamamoto theory; the theory or assumptions used in the theory may be inadequate; or measurements given by the instrument may be in error. All four reasons are now being investigated.

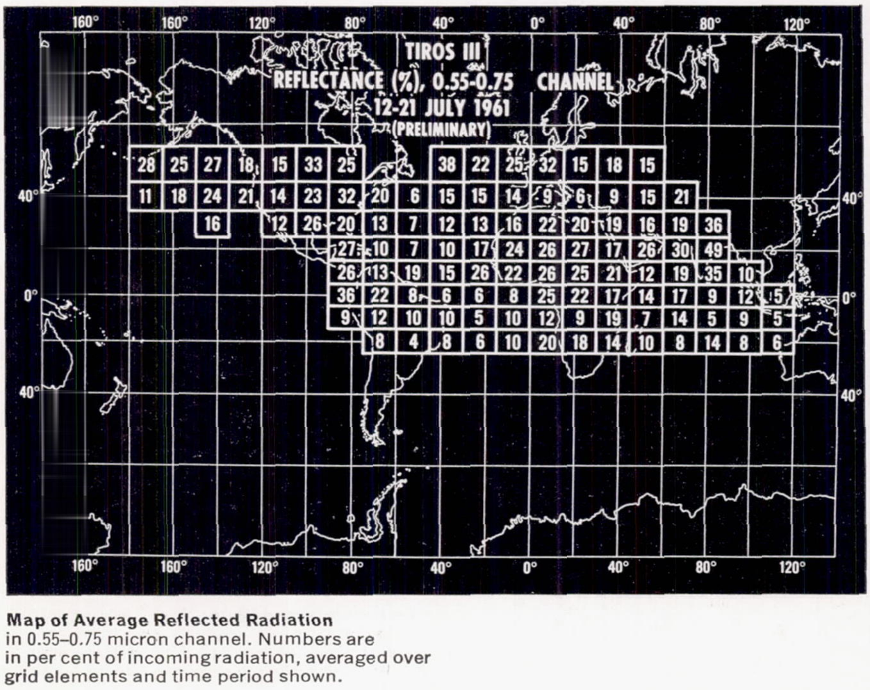
An increasing deterioration in the response of all channels of the radiometer with flight time was found in Tiros II and to a greater extent in Tiros III.[16] However, corrections to account for this change in calibration are already incorporated in the temperature difference stated above. Results of further theoretical investigations and elaboration of the above reasons will certainly provide more precise methods of cloud height determinations from radiation measurements. In addition, these investigations, combined with a more complete scrutiny of all the data available, will shed light on such unknowns as the emissivity of various types of clouds and the screening effect of aerosol or similar particles on the outgoing radiation. Nevertheless, empirical correction factors can be obtained even now from existing data and successful, if approximate, determination of cloud-top heights may be and have been made from Tiros measurements.[23]

Similar considerations govern our ability to derive pertinent information on the structure of the atmosphere from radiation data. An example is given in the illustration on page 80. By comparison of the black-body temperatures measured in the 8–12 micron window channel over hurricane Anna (200–210 K) with simultaneous measurements in the 6.7 microns water vapor absorption channel indicates that the temperatures measured in the latter are approximately 10 K higher. Since we have already determined from the window channel that the cloud tops reached to approximately 15 km (near the tropopause), this temperature difference can only be explained by the presence of considerable amounts of water vapor in the stratosphere above the cloud top.

Bandeen, et al.[9] have found by trial and error a water-vapor distribution which will produce this measured temperature difference. The required water-vapor mixing ratio vs. altitude function is shown in the illustration on page 80. This function is by no means unique but was chosen because it agrees both with present ideas of water-vapor content in the stratosphere[25] and with the radiation measurements. Again, the above case is typical for several situations observed so far over extensive cloud systems in the tropics and is indicative of some of the more subtle information contained in these results.

Attempts to derive estimates of the global heat budget from radiation data have been made and investigations by Winston and Rao,[8] Bandeen and Nordberg,[5] Prabhakara and Rasool,[6] and House[7] have shown that on a large scale the satellite results confirm theoretical estimates by London[24] and others on the global distribution of total emitted long-wave radiation. The satellite investigations are based on Explorer VII measurements[26] and on the 8–30 micron channel from Tiros II and III.[5,6,8] An example is shown in the graph on page 80. Tiros II data shown in this figure have been corrected for the deterioration of the sensor response with time and for total outgoing flux by the method of Wark and Yamamoto.[22]

The Tiros results show clearly, although not to the extent predicted by theory, a minimum of outgoing radiation near the equator. This minimum is due to the extensive cloud cover in the equatorial zone, while the maxima near the two tropics reflect the clear skies and warm temperatures of these regions. The more rapid decrease of outgoing radiation with latitude in the winter hemisphere, due to colder temperatures and intenser cloudiness, as well as the higher maximum near the summer tropic, can be clearly found in the satellite data. Investigation of outgoing radiation on a shorter time scale based on Tiros II measurements, and comparisons with dynamic considerations of the atmosphere, have shown that in some cases minima in outgoing flux go hand in hand with



Map of Average Reflected Radiation
in 0.55–0.75 micron channel. Numbers are in per cent of incoming radiation, averaged over grid elements and time period shown.

an increase in the zonal kinetic energy which is derived from, and is a measure of, the energy carried by winds along a latitude circle.[8] This first indication of a connection between the gross outgoing radiation measured by satellites on a planetary or continental scale and energy parameters relating to the dynamics of the atmosphere will be further pursued, and is of major importance to an understanding of the forces which create circulation in the atmosphere.

A complete planetary heat budget, however, must include a measure of incoming solar radiation in addition to outgoing long-wave radiation. Measurements from one of the Tiros III solar radiation channels (0.55–0.75 microns) of regional averages of reflected energy over a period of nine days are shown in the illustration on page 81. The numbers express the total energy reflected in percent of incoming solar radiation within the spectral range of the instrument. This incoming radiation was taken to be (108.6 w/sq meter) sin *e*, where *e* is the elevation angle of the sun at the location and time of measurement. The value of 108.6 is derived from a total solar constant of 1395 w/sq meter and the spectral response for this channel.[16]

The illustration shows that radiometric measurements in the visible spectrum again reflect very well the distribution of cloud cover—namely, high average reflectivities near the equator and low ones in the subtropics, except for India, where during this time of the monsoon the highest average reflectances (49%) were observed. The differences in average reflectances between land and water at moderate latitudes only may also be seen in this illustration. Reflectances over the subtropical North and South Atlantic, the Indian Ocean, and the Mediterranean are appreciably lower than over land masses at comparable latitudes. Apparently, in these regions differences in the reflectances of land and water surfaces are noticeable because of the predominantly clear weather. At higher latitudes, like the North Pacific, no difference in reflectance can be detected, apparently because cloud cover is more frequent over water than over land.

In addition to supplementing the cloud cover patterns observed during daytime in the infrared window, which is not well suited to detect low-altitude clouds, the solar radiation channels on Tiros can be used to derive *relative* measurements of the absorption of solar energy and aid in interpretation of long-wave outgoing flux measurements.

The illustration also shows that measured reflectances cannot be interpreted as measurements of planetary albedo, and are therefore not useful to include in quantitative heat budget considerations at this time. Since the solar constant is known quite accurately and the outgoing flux is given in the graph on page 80, we know that, for the sake of equilibrium, the sum of the average planetary albedo and the outgoing radiation must equal the incoming solar radiation. This results in a value of 32 to 36% for the average albedo. The average found from the illustration is 17 to 18%.

This disagreement by a factor of 2 is difficult to explain, particularly since the deterioration in the response of the sensors[16] has already been taken into account. The fact that Tiros measurements for this period cover only a limited region of a zone between 55° N and 25° S may influence the results somewhat, but certainly not to such a large extent.

A more likely explanation may lie in the fact that the values in the illustration are based on isotropy and uniformity with regard to both the angle and wavelength of the backscattered sunlight. There are indications from theoretical investigations[20] that the reflectance toward the direction of the incoming sunlight may be appreciably larger than in other directions. Since in most of the observations used in the illustration, the angle formed by the sun, the target, and the satellite was near 45 deg, it is possible that this might account for the low observed reflectances. A variation in the reflectance with wavelength may also contribute to make the satellite observations appear too low.

These factors are now being investigated both theoretically and by supplementary laboratory and free atmosphere balloon measurements.

Conclusions. Thus, maps of cloud patterns revealing meteorological features such as frontal systems, tropical storms, etc., have been produced with adequate resolution and in large quantities from the Tiros radiometric experiments to demonstrate their value to both day and night synoptic analysis. With appropriate, empirically derived, correction factors, one can also obtain approximate measurements of cloud heights, especially over large, uniform, and intense cloud systems. Successful determinations of the global distribution of total emitted long-wave radiation over limited periods of time have been made and agree well with theoretical predictions. Some preliminary correlations were found between outgoing fluxes and dynamic parameters in the atmosphere.

Reflected solar radiation, measured to permit an evaluation of the entire planetary heat budget, follows very closely, as one might expect, the patterns of cloudiness, as well as the distribution of land and water—at least over those regions of the globe covered by Tiros. Quantitative measurements of the earth's albedo, however, have not been possible as yet.

The difficulties which now prevent us from interpreting solar-energy reflectance measurements in terms of albedo and the disagreement found between calculated and measured emitted radiation in the window channel will certainly force us to subject measurements to further interpretations. From these we may find further enlightenment regarding the large-scale scattering, emission, and transmission properties of clouds, the earth's surface, and the atmosphere—parameters which may still lie dormant in a vast amount of data. We believe that, with the successful interpretations of the radiometer measurements mentioned earlier, we have only exploited a small, more obvious portion of the data.

It has also been shown that under certain circumstances the presence of substantial amounts of water vapor in the stratosphere can be implied from simultaneous radiation measurements in two spectral channels. Again, resolution of some of the outstanding theoretical questions will produce more information on water-vapor distribution both in the troposphere and stratosphere.

Tiros radiation measurements have also pointed up the need for an improvement in the stability of optical sensors under prolonged flight environment. Deterioration in sensor response during orbital flight has not been fully explained. This further emphasizes the need for reliable in-flight calibration on future instruments. And, finally, support of satellite experiments with coordinated ground-based or balloon measurements have become even more important.

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