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Image Sensing as Applied to Meteorological Satellites

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Earth satellites provide meteorology with an observing platform commensurate with the global nature of weather. One of the most promising satellite observations is of cloud distribution and type. Several image-sensing systems are being considered. Cloud images, both day and night with a resolution of about 0.5 mile, are ultimately desired. Problems in sensing instrumentation, communications, processing and data presentation must be solved before an operational system becomes a reality.

EVEN WITH THE RAPID advances in meteorological observations during recent years, only a small percentage of the Earth's atmosphere is adequately probed by conventional meteorological observations. Thus, large storms can reside undetected for days in many desert, polar and oceanic areas of the world. Even in areas having dense meteorological networks small storms are probably often not detected.

Conditions in the atmosphere in one region of the Earth may influence the subsequent weather conditions in a distant part of the Earth's atmosphere. These atmospheric interactions, global in nature, require an observing system which is global in scope. The artificial Earth satellite offers the meteorologist an observing platform which will permit every point on the Earth's surface and in the Earth's atmosphere to be observed at frequent intervals.

The Earth's weather is determined primarily by conditions existing in the lowest 40 miles of the atmosphere, far below usual satellite altitudes. Therefore, meteorological satellite observations so far suggested depend on some type of radiation measurement such as solar radiation reflected, and infrared radiation emitted, by the Earth and atmosphere, or electromagnetic radiation emitted from a satellite and reflected back by the Earth and atmosphere. Many of these measurements involve image sensing. Indeed, the application of image sensing to cloud and precipitation detection appears to offer the best possibility for the first operational use of meteorological satellite observations.[1] Thus, considerable emphasis is being placed on the development of techniques for obtaining cloud images from satellites at night

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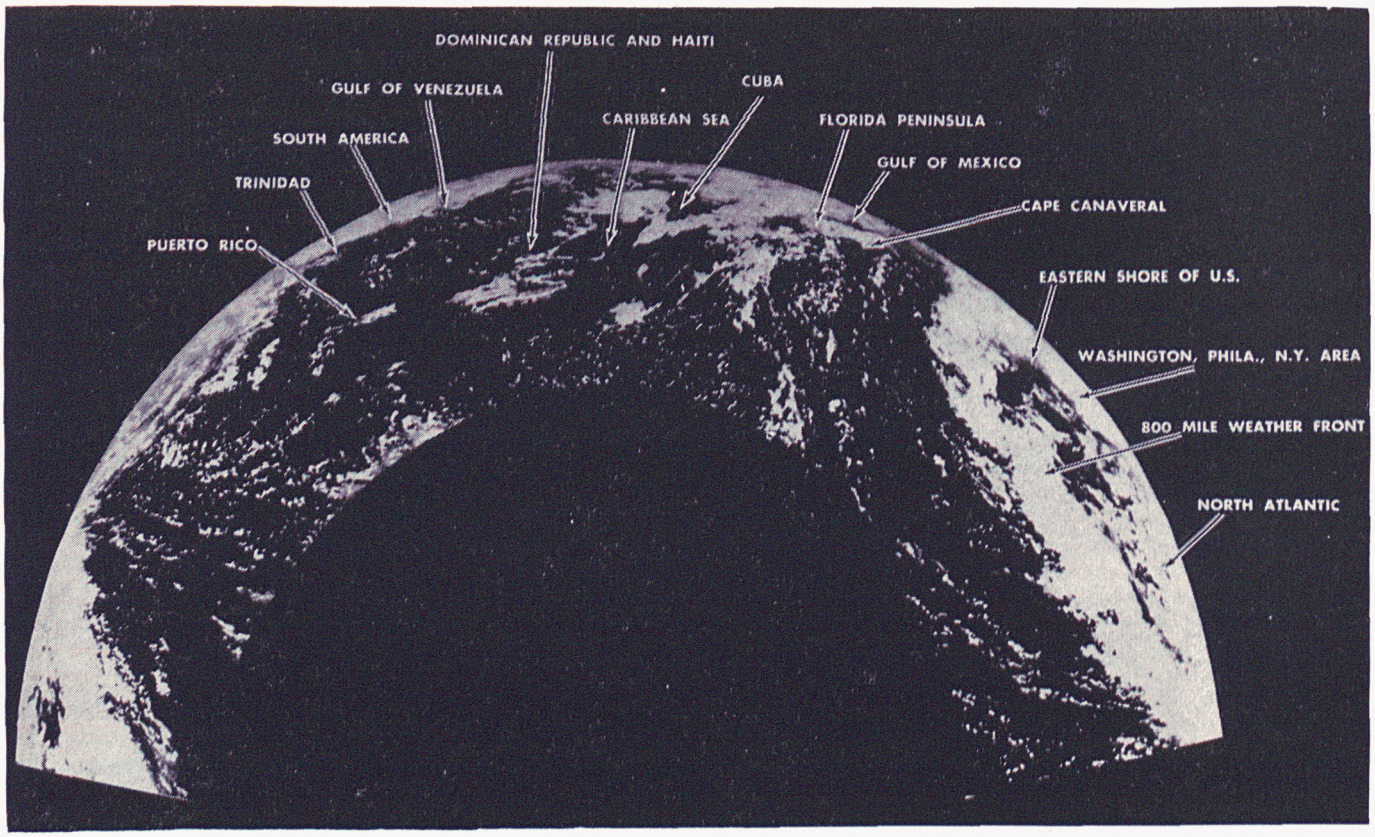

Fig. 1. Cloud mosaic obtained from a rocket flight southeast of Florida on Aug. 24, 1959. The camera was at an altitude of 300 to 400 nautical miles when these pictures were taken. (Mosaic prepared by Missiles and Space Div., General Electric Co., Philadelphia.)

as well as in daylight and on the use of radar to obtain images indicating areas of rain and snow.[2,3]

Image-Sensing Requirements

To obtain global coverage at frequent intervals, Earth-oriented satellites in quasi-polar orbits are required, equipped with sensors which can provide useful information both night and day. The image sensors must view an area determined in one dimension by the distance on the Earth's surface at the equator between adjacent orbits. For example, for a satellite at an altitude of 800 nautical miles, this distance is about 1730 nautical miles and defines an included angle of view of about 87°.

It is difficult to define the resolution required in cloud imaging for meteorological applications. This is due both to the problems of "seeing" for target identification and the variation in information content required for different meteorological applications.

Target or cloud recognition is a function of the relative contrast between the target and its background as well as the resolution and available illumination. Clouds must be observed against a background of the Earth's surface. The reflectance or albedo in the visible part of the spectrum for the Earth's surface varies from as low as 3% for water with solar elevation angle greater than about 30° to over 80% for a fresh snow surface. Cloud albedo varies from less than 10% to more than 80% depending on cloud type and thickness. Therefore, in many cases, the brightness contrast may be quite small and even zero in some cases. The effect of atmospheric scattering on brightness contrast is discussed later. As the brightness contrast decreases, higher resolution is required for the eye to just identify a specific target.

Resolution. Consider next the resolutions dictated by meteorological requirements, assuming that all clouds can be distinguished from their backgrounds. At least three types of information are desired from cloud images obtained by satellites: first, the determination of the percentage of a given area covered by cloud; second, overall cloud patterns or orientations such as vortices and lines of clouds or cloud "streets"; and third, the determination of cloud type by its shape, size, texture and distribution. Each of these, to some degree, places different requirements on resolution. A reasonable measure of cloud amount, averaged over an area of at least several hundred square miles, can probably be obtained with a resolution as poor as two or three miles. Cloud patterns or orientations can be determined with reasonable certainty, in many cases, with a resolution of about one to two miles. Better resolution may be required where cloud elements are viewed at an oblique angle. Considerably better resolution will often be required to determine cloud type.

There is, at present, considerable conjecture in arriving at values of resolution required for meteorology. We are used to observing clouds by viewing them from below. It is only very recently that research meteorologists have had a downward view of clouds over large areas by means of rocket photography and we have yet to obtain useful cloud images from satellites. Therefore, the meteorologist must gain new experience before arriving at any precise determination of the resolutions required in cloud imaging from satellites.

Cloud photographs obtained from high-altitude rockets and missiles, such as the one shown in Fig. 1, are now being studied to define more precisely the resolutions required. Preliminary results indicate that with a reasonably high contrast ratio, a resolution of about one mile is adequate for many meteorological applications. With a resolution of only two miles, some details are lost, although much valuable meteorological information is usually retained. Resolutions better than one mile provide additional cloud information although the maximum desirable resolution has not been precisely determined. At present, it is believed that ultimately a resolution of at least one-half mile, not considering brightness contrast, is desirable.

The geometry of the object field enters into the determination of the system resolution. The satellite is viewing the Earth's curved surface. As mentioned earlier, an arc on the Earth's surface about 1730 nautical miles long normal to the satellite's orbital velocity vector must

be included in the field of view from a polar orbiting satellite 800 nautical miles above the equator to obtain full coverage of the globe. To obtain the desired resolution of one-half mile at the edge of the object field, 865 miles from the satellite sub-point, an angular resolution of about 0.012° would be required. This angular resolution would give a linear resolution on the Earth's surface at the satellite sub-point of 0.16 miles.

Sensitivity. The sensitivity and dynamic range of image sensors is of considerable importance. The meteorological requirement in this regard is simply stated: "We want to 'see' all the clouds all of the time." However, it is quite difficult to convert this to meaningful engineering requirements. Several factors must be considered. For example, the type of image-sensing system is important, such as a system sensitive to reflected solar radiation as compared to one responding to self-radiation in the infrared. The range in contrast between target and background is important as is the albedo and radiational properties of both the target and background. Scattering and attenuation in the atmosphere between the object field and the satellite must also be considered.

Utilizing radiation in the visible part of the spectrum, the meteorologist ultimately would desire a sensor which could detect clouds when illuminated by sunlight, moonlight, or even starlight. This represents a fantastic range in incident illumination.

The radiation received by a unit area at the Earth's surface decreases as the angle of incidence departs from normal due to the cosine law and the incident radiation having had a longer path through the atmosphere. For example, the direct solar radition received on a unit horizontal area at the Earth's surface with a solar elevation angle of 18° is about two-tenths that which would be received by the same area with the sun directly overhead.

While atmospheric scattering reduces the amount of energy received by the satellite from the target, it also reduces the relative contrast between the target and its background. This is a particularly serious problem for targets located on the Earth's surface where the light reflected by both the target and the background are subjected to the same amount of scattering. In cloud identification the problem is not nearly as severe. The particulate scattering decreases quite rapidly with height above the earth's surface. Most clouds have tops which are at least 5,000 ft above the Earth's surface. Also, in many cases, the cloud tops are associated with a temperature inversion which tends to limit the majority of the particulate matter to the atmosphere below the inversion. Therefore, in general, the radiation reflected by the cloud tops will be subjected to considerably less scattering than that reflected by the Earth's surface. The effect of molecular, or Rayleigh scattering, can be minimized by filtering out the blue part of the spectrum. As a result, in most cases the relative contrast between the clouds and their backgrounds should not be seriously reduced by scattering. However, particulate scattering will increase the effective albedo of the background. In the case of sensors depending upon solar radiation, the relative contrast can be increased by limiting the spectral response of the sensors. Some experimental evidence[4] suggests that a 0.2-μ interval centered at a wavelength of about 0.65μ would provide the optimum relative contrast, considering the wide variety of backgrounds, including oceans and vegetative matter, which will occur. Of course, limiting the spectral interval will require greater system sensitivity.

Infrared. The previous discussion has been concerned with image sensors responding to radiation in the visible portion of the spectrum. Somewhat similar problems must be considered in the case of infrared image sensors. In this case, imaging depends upon differentiating the radiation emitted by clouds from that emitted by the background. The relative contrast is diminished by the radiation also emitted from the atmosphere.

The amount of energy emitted by an object is a function of its emissivity and temperature. As an approximation, many clouds and the Earth's surface can be considered blackbodies (emissivity of one). The difference between cloud top and Earth temperatures will largely control the contrast between the desired image and its background. In polar areas, low clouds are often warmer than the surface beneath while in tropical and temperate zones, clouds are generally colder than the Earth's surface. On some occasions, there may be no difference between the cloud top temperature and the Earth's surface temperature.

The atmosphere, particularly water vapor, carbon dioxide and ozone, also emits radiation in the 5- to 30-μ region. This radiation reduces the relative contrast between the cloud top and the underlying Earth's surface.

The problems of infrared image sensing are covered in more detail in a paper by Hanel and Stroud.[5]

Cloud Image-Sensing Techniques

Object Scanning. The simplest form of image sensing utilizes mechanical or object scanning induced by the motion of a spinning satellite. Such a system was used in the Vanguard II cloud cover experiment devised by Stroud and his associates while at the U.S. Army Signal Research and Development Laboratories.[6,7]

In this first attempt at image sensing from an Earth satellite an optics-sensor system was utilized having an included angle of view of one degree and sensitive to radiation between about 0.6- and 0.8-μ wavelength. Two sensors were utilized pointing in opposite directions with their optical axes 45° from the satellite spin axis. As the spinning satellite moved in its orbit one of the two sensors would scan the Earth's surface. With the proper spin rate and altitude the individual scan strips would be contiguous. The output of the sensors was amplified and the information stored on a magnetic tape recorder for relay to the Earth when the satellite was interrogated by a ground station.

For optimum results this system requires a nearly circular orbit, stable spin axis, and a spin rate determined by the angular resolution of the optics and the altitude of the satellite. In the case of the Vanguard II experiment the orbit was quite elliptical, the spin axis had large perturbations and the spin rate was considerably less than the design value. Therefore, even though the instruments worked perfectly, it has so far not been possible to reconstruct the data in the form of cloud photographs.

The basic simplicity of this system has considerable merit. It deserves further consideration when satellite motions can be precisely controlled. Alternatively, the system could be used by providing mechanical scanning on an Earth-oriented satellite where the satellite axis is normal to the Earth's surface and there is no rotation of the satellite about this axis. However, considerably better resolution is desired than that used in the Vanguard II experiment. With the development of instruments with high sensitivity in the infrared region of the spectrum, this type of system offers promise for cloud imaging at night as considered by Hanel and Stroud.[5]

While a mechanical-scanning system simplifies the instrumentation in the satellite, it adds to the complexity on the ground. The scan information must be properly reconstructed in picture form and located with respect to the Earth's surface. The data, to be of operational value in meteorology, must be rapidly converted to usable form after receipt on the ground. Particularly in the case of a spinning satellite, all of the orbital parameters would have to be known precisely ahead of time in order to meet this time requirement.

Electronic Image Scanning. Some of the problems of the mechanical scanning system can be overcome by the use of electronic image scanning. An instantaneous view of an area on the Earth's

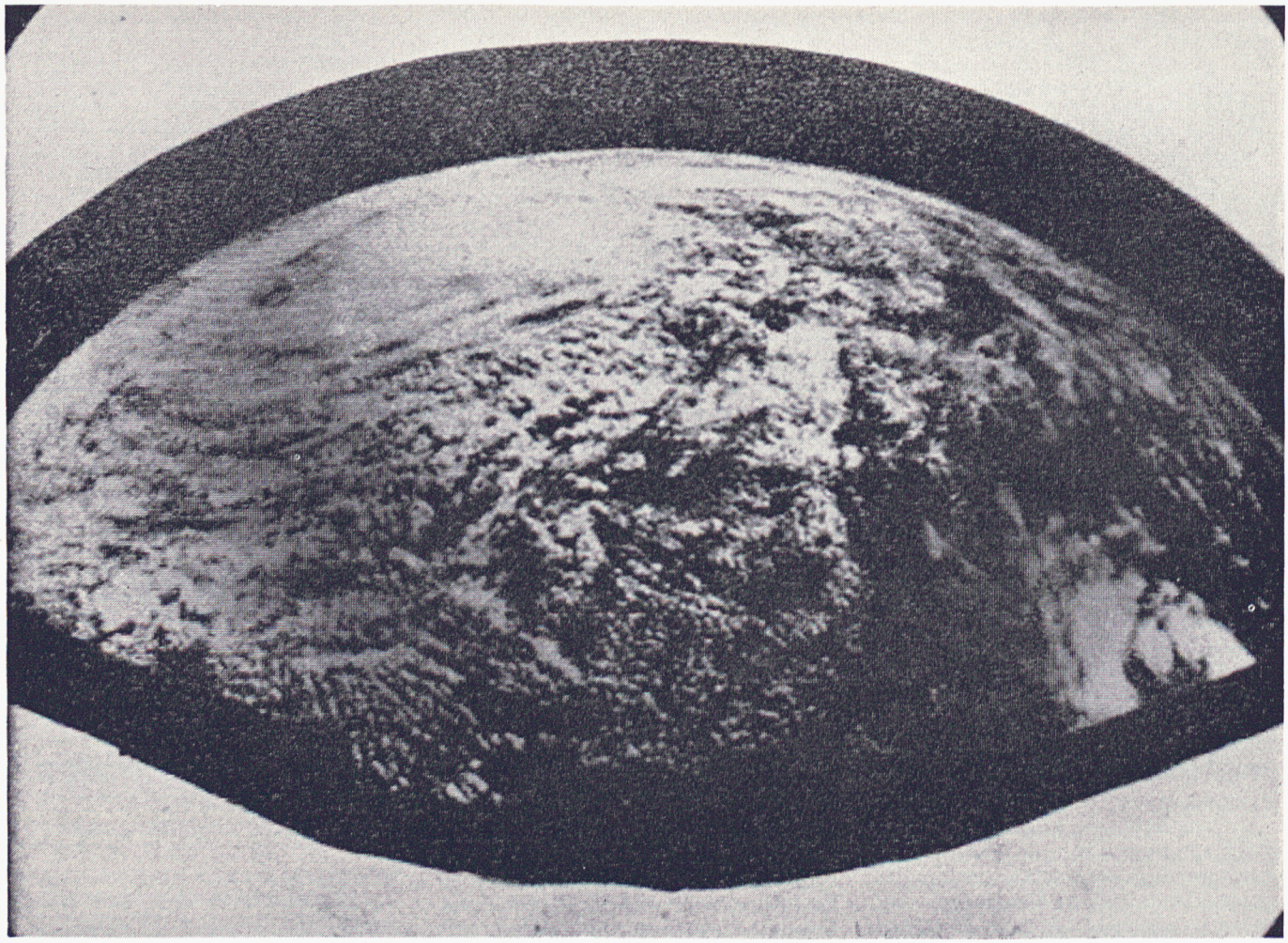

Fig. 2. Simulation of type of picture which might be obtained with image scanning, based on rocket photos taken at about 80 nautical miles above White Sands, N.M. (Original photo by U. S. Naval Research Labs., simulation by Astro-Electronic Products Div., Radio Corp. of America.)

surface can be imaged on the photosensitive surface of a photoconverter tube such as a vidicon or image orthicon and an electron gun used to scan this image plane.

While knowledge of the motions of the optic axis of the imaging system is still required to locate the resulting cloud picture with respect to the Earth's surface, this need be done only once for each picture. In addition, information in the pictures themselves will assist in this location process. This image-scanning system has the further advantage that the pictures can be reconstituted rapidly after receiving the signals at the ground.

Figure 2 is a simulation of the type of picture which might be obtained with an image-scanning system. The original cloud mosaic was prepared from a series of photographs taken at an altitude of about 80 nautical miles on a rocket launched from White Sands, N.M. The mosaic was scanned electronically, using a 21-db signal-to-noise ratio, and the resulting image displayed on a television monitor and photographed.

The spacing between adjacent scan lines in the center foreground is equivalent to about one mile on the ground. The distance between line pairs increases as one approaches the horizon, probably averaging more than ten miles in the upper part of the picture. Even with this resolution, many of the major cloud features are retained.

While Fig. 2 approximates the resolution which may be obtained from early meteorological satellites, improvements in sensors, data storage and communications should eventually permit the optimum coverage and resolution desired by meteorologists.

With present electronic scanning systems we are limited to daylight operation. However, recent laboratory results hold considerable promise for the application of high sensitivity, image-orthicon or image-converter tubes for nighttime use, at least with moonlight. The possibility of high-resolution nighttime cloud observations warrants their serious consideration for meteorological satellites.

Electrostatic Imaging and Recording. A serious problem in cloud imaging from satellites is the storage of the video data for subsequent playback when the satellite is within contact of a readout station. Magnetic-tape recorders are presently used on many satellites; however, it is doubtful that this storage medium is practical for a system which would meet the ultimate meteorological requirement of worldwide coverage and a resolution of about $\frac{1}{2}$ mile. Current laboratory work utilizing electrostatic tape as a storage medium indicates a promising solution to this problem. Also the electrostatic tape can serve as the photosensitive surface.

It appears that this electrostatic system, combined with a suitable optical system, can come close to meeting the ultimate in meteorological requirements, at least for daytime operation. The work of one laboratory in this area is reported by Hutter, Inslee and Moore.[8]

Data Storage, Transmission and Processing

While the primary subject of this paper is image sensing, the problems of storage, transmission and processing of the sensed information must be recognized as they are of comparable magnitude to the problems involved in the image sensing itself.

For example, a polar orbiting satellite at an altitude of 800 nautical miles, viewing a strip on the Earth's surface 1750 miles wide, with an angular resolution of 0.012° both day and night, would result in approximately 10^9 bits of data being collected during one orbit. Since it is not practical to read out these data more frequently than once per orbit, all these data must be stored for subsequent playback. A storage medium of high packing density is required for compatibility with the size and weight limitations of satellites which will be available in the near future. A maximum of about 10 min would probably be available for the readout of these stored data, requiring a bandwidth of about 1.7 mc.

After signals are received on the ground they must be processed rapidly and the cloud information located with respect to an Earth coordinate system so that the meteorologists can utilize the data. This is difficult to accomplish at present with the use of spin stabilized satellites generally in elliptical orbits. The use of stabilized Earth-oriented satellites in circular orbits would simplify the picture location problem. It should even be possible to develop a nearly automatic system for processing and locating the cloud image data.

Unfortunately, the readout stations usually are not located where it is desired to use the meteorological satellite data. Therefore, it is necessary to transmit this information to various points on the Earth where it is required. For example, the Weather Bureau's National Meteorological Center is located in Washington, D.C. For full operational utilization of the cloud image data it will be necessary to transmit the information from the readout stations to this center.

Initially, it probably will be necessary to have meteorological groups at each of the readout stations perform a preliminary analysis of the cloud pictures obtained. The results of these analyses could then be transmitted to various meteorological centers by either facsimile or teletype. Ultimately, communication satellites may provide a means of transmitting the picture information directly to meteorological centers for analysis.

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