A PILOT STUDY ON THE APPLICATION OF GEOSYNCHRONOUS METEOROLOGICAL SATELLITE DATA TO VERY SHORT RANGE TERMINAL FORECASTING

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1225 West Dayton Street
Madison, Wisconsin 53706

Contract No. F19628-70-C-0207
Project No. 8628
Task No. 862811
Unit No. 86281101

FINAL REPORT
Period Covered: 1 April 1970 through 31 August 1970
30 September 1970
Contract Monitor: John H. Conover, Meteorology Laboratory

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ABSTRACT

The study assembles a unified body of data consisting of very high space and time resolution reflected radiance measurements from a geosynchronous satellite (ATS-III) along with concurrent meteorological radar, ceiling, visibility and surface pressure reports at selected air terminals in the central United States. This data set allows familiarization with the meteorological potential of nearly continuous observation of cloud conditions from a geosynchronous platform. It may also serve as initial input to quantitative techniques for evaluating the satellite data and/or for testing its usefulness in very short range weather forecasting. In this regard, a second portion of the study presents arrays of statistical descriptors of the satellite data.
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1.0 Introduction

The purpose of this pilot study is twofold:

(a) to assemble a unified body of data from both geosynchronous satellite measurements and conventional meteorological observations in order to allow a test of the usefulness of the new type of satellite data for improving terminal ceiling and visibility forecasts;

and

(b) to experiment with the construction of arrays of quantitative descriptors of the satellite radiance measurements in anticipation of the potential use of such parameters as predictors in a statistical relation designed to allow the test of forecasting improvement mentioned above.

Thus the pilot study is aimed as a first, new look at an existing problem of weather forecasting. Results of the study will aid decisions on both the course and the magnitude of subsequent work, if any. This new work may extend to other meteorological applications, in addition to terminal forecasting. A new look is possible because of the availability of the measurements from a geosynchronous satellite, ATS-III.

Only in recent years have the data from NASA's Applications Technology Satellites I and III allowed nearly continuous views of changing cloud patterns related to the real-time weather. This is possible, because the satellites are in geostationary orbit, at altitudes near 22,000 miles, and thus orbit the earth's equator with a period of 24 hours, the same rotation as a point on the earth's surface. In addition, the experiments on these satellites were designed to obtain high precision measurements of reflected solar radiation from spots on the earth as small as 2 miles (1, 2, 3).

From the existing archive of ATS satellite data stored on tape, three days were chosen for the pilot study. On these days successive satellite measurements and weather station observations were collected over and around three terminals of interest. Analyses were prepared
of the satellite radiance fields, radar observations, ceiling and visibility reports, and surface pressure measurements. A sampling of these analyses as well as special time-distance cross-sections of the same parameters are presented in this report. The remainder of the nine cases studied is available for future use, as required. In like manner, only selected examples of the satellite data statistics are presented for illustration of their potential.

Results of the pilot study are encouraging and suggest several possible new areas of application of the geosynchronous satellite measurements. Furthermore, they indicate that it should be profitable to proceed to the actual test of a significant sample of cases like those in this study in order to evaluate the use of such satellite data for improving air terminal forecasts. Such very short range predictions are a form of quantitative "now-casting" (i.e., forecasting from a continuously updated set of initial values).
2.0 Preparation of the Data Set

The pacing item for case selection was the few number of days during 1968 and 1969 when the ATS satellite data were available on tape in a nearly unbroken time sequence. Together with the requirement to view active weather patterns over the United States, this fact focused our selection of case days to those when a "severe weather alert," a period of special data acquisition, occurred.

2.1 Use of geosynchronous satellite data

During the spring of 1968 and 1969, NASA's geosynchronous satellite ATS-III was positioned at longitudes giving the spincan camera experiment on board a good view of the United States during all the daylight hours. This experiment, a set of photomultiplier tubes behind a small telescope (1, 2), obtained reflected solar radiance measurements as it scanned the earth's disc. West-to-east scans resulted from spacecraft rotation, and a north-to-south scan was forced by mechanical stepping. After transmission and digitization, one frame (one picture of the illuminated earth disc) is composed of 2408 scan lines with 8192 samples (elements) per line. Each sample has 8 bit precision (levels from 0-255 digital counts). These digital counts are directly proportional to the voltage output of the "camera" and, in turn, to the reflected radiance (3) arising from the camera's field-of-view (0.1 milliradians). Near subpoint of the spacecraft this field-of-view is equivalent to a ground resolution of about 2 nautical miles from spacecraft altitude.

After processing at NASA's ground station at Rosman, N. C., the tapes containing the satellite experiment signal were sent to the University of Wisconsin for use and archiving. Because of some difficulty with the analog recorded during the period of interest to this study, only those tapes digitized at the ground station were chosen for use. Following checks of tape quality, three days were selected

\[1\] Since May 1969, a new analog recorder has removed this limitation on the use of precision ATS data.
for this study: April 19 and 23, 1968, and April 4, 1969. The total number of tapes (pictures) and the time interval covered on each day were as follows:

<table>
<thead>
<tr>
<th>Date</th>
<th>Time Range</th>
<th>Duration</th>
<th>Tapes</th>
</tr>
</thead>
<tbody>
<tr>
<td>April 19, 1968</td>
<td>2156-2318 Z</td>
<td>1 1/2 hr</td>
<td>4</td>
</tr>
<tr>
<td>April 23, 1968</td>
<td>1701-1946 Z</td>
<td>2 1/2 hr</td>
<td>5</td>
</tr>
<tr>
<td>April 4, 1969</td>
<td>1428-1948 Z</td>
<td>5 1/2 hr</td>
<td>8</td>
</tr>
</tbody>
</table>

Although the time intervals to be studied were less (in two cases) than planned, the ATS data coverage is still much greater than that provided by a "snapshot" from a polar orbiting satellite.

In digital form, one frame of ATS-III data from the spinscan camera fills one reel of high-density tape. To minimize data handling, only a region enclosing most of the United States was chosen for further processing, data "navigation" and "normalization" to an earth-located reference. This was done according to a procedure designed by Smith, Phillips, and Vonder Haar.\(^2\) The technique uses recognizable landmarks within the ATS data array to derive the orientation of the satellite's spin axis. Together with a knowledge of satellite ephemeris, the transformation from satellite coordinate system (line-element) to earth coordinate system (latitude-longitude) is a matter of geometry. The technique is very similar to one reported in (4). The resulting best-fit of landmarks gave all cases a relative alignment error of ±10 nautical miles maximum over the region of interest. Actual construction of the normalized ATS data field requires a great deal of array interpolation and averaging within the computer (UNIVAC 1108 and CDC 3600).

Following normalization and selection of specific terminal areas (see 2.2), the reflected radiance values (in terms of digital counts) were objectively analyzed on an x-y plotter at nine contour levels (i.e., 15, 30, 45, 60, 75, 90, 105, 120, 130). These were chosen after view of the relative variation across the scene shown in the first picture of each daily sequence. Since reflected radiance from a cloud changes due to variations in the angular reflection characteristics as well as because of physical changes in the cloud itself,

\(^2\) Unpublished report.
contour values of all frames after the first in the day were normalized according to a bi-directional reflectance method of Marshall and Vonder Haar. It is based on work done as an aid to interpreting NIMBUS satellite data (5, 6). The normalization factors vary slightly with location during a particular day. However, for the frames and days used in this pilot study, the normalization ranged from 7 per cent at the minimum to a factor of two within a daily sequence.

It is important to note that the brightness normalization applies only to variations within a given day and allows intercomparison of reflected radiance measurements from clouds with high relative accuracy within that day. Additional factors must be considered in establishing relative accuracies from one day to another. These include: (a) location (subsatellite point) of the satellite (b) spacecraft camera gain settings (c) spacecraft/ground station telemetry link (d) gain setting of video processor and recorders on the ground.

Without a reference signal injected at the spacecraft instrument and carried throughout the downlink onto digital tape, day-to-day variation in (a) thru (d) above precludes day-to-day comparision of radiance values without additional checks. During the time periods used in this pilot study, the experimental ATS-III satellite system and spinscan experiment were subject to several adjustments (not always completely recorded). In addition, a reference level was not available. Since the major emphasis of the pilot study is on variations at an air terminal within a given day, the after-the-fact relative calibration checks were not performed.

3 Unpublished report. (see appendix A)

4 The relative calibration checks are best done during the navigation and normalization phases of data reduction when selected portions of the image frame are used for earth location. They may include the following: significant samples of clear ocean and/or land surfaces (i.e., Sahara region, White Sands, or salt flats) under the same angular conditions; and/or limb radiance, lunar, space level, or integrated frame brightness values.
In addition to assembling an important part of the data set for this pilot study, work with the geosynchronous ATS data broadened the experience base and contributed a great deal to current techniques for landmark identification, use of navigation programs, and preparation of normalized data. It was very nearly a pioneer effort in ATS data application.

Figures 1, 2, and 3 (a, b, and c respectively) show reproductions of one selected frame of ATS data for each day of the pilot study, a closeup of the United States' area, and a view of the area for which normalized data were derived.

2.2 Selection of terminals

A display of the synoptic weather situation in the early morning hours on each of the three days of the pilot study is shown in Figures 4a, b, and c. Since we wished to acquire a good range of ceiling and visibility occurrences for the data set, three areas (of 100 mile radius) were picked for each day. These regions surround a "central" air terminal; two have significant weather with one relatively clear. Other factors influenced the choice of terminals in this pilot study. They were:

(a) areas were restricted to the normalized portion of the tapes (see Figures 1c, 2c, and 3c).

(b) good radar coverage was required for comparison purposes.

(c) The "central" terminal should be flanked by a sufficiently dense and well-distributed network of supporting stations that record visibility, ceiling, surface pressure, and other synoptic variables.
The following were chosen for use:

<table>
<thead>
<tr>
<th>Date</th>
<th>Central Station</th>
<th>No. of Stations in Group</th>
<th>No. of Available Radars Covering Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>April 19, 1968</td>
<td>Omaha, Neb. OMA</td>
<td>13</td>
<td>2</td>
</tr>
<tr>
<td>&quot;</td>
<td>Wichita Falls, Tex. SPS</td>
<td>12</td>
<td>3</td>
</tr>
<tr>
<td>&quot;</td>
<td>Springfield, Mo. SGF</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>April 23, 1968</td>
<td>Columbia, Mo. CBI</td>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td>&quot;</td>
<td>Columbus, Ohio CMH</td>
<td>11</td>
<td>3</td>
</tr>
<tr>
<td>&quot;</td>
<td>Meridian, Miss. MEI</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>April 4, 1969</td>
<td>Meridian, Miss. MEI</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>&quot;</td>
<td>Ft. Wayne, Ind. FWA</td>
<td>16</td>
<td>3</td>
</tr>
<tr>
<td>&quot;</td>
<td>Dodge City, Kan. DDC</td>
<td>6</td>
<td>2</td>
</tr>
</tbody>
</table>

Figure 5 shows the location of the selected stations.

2.3 Conventional meteorological data

The rationale for forming the present study over regions of the United States having a high density of weather reporting stations was to allow detailed comparison of the ATS satellite observations with more conventional meteorological reports. As mentioned in 2.1, there are no gaps in the satellite's areal coverage with ground resolution of 2-3 miles. Except in special cases we can expect synoptic weather reports to represent a region larger than this about the pertinent station. Allowing for some small uncertainty in location of the satellite data, it is apparent that comparison of a slightly smoothed field of satellite measurements at full camera resolution with concurrent meteorological observations should work very well.

Data were obtained on microfilm from the National Weather Records Center. These included the hourly and three-hourly surface weather reports as well as reproductions of the filmed weather radar scopes. In all cases, the conventional meteorological data were selected at
times closest to the time of the appropriate satellite measurement. The time differences did not exceed 10-15 minutes for the surface weather reports and were even less for the radar coverage.

Prints of radar images were made and the portion of the radar screen which covered each station group marked on the prints (Figure 6). The radar range was commonly 250 miles, thus allowing a station group to be completely depicted within a radar photo, provided the radar station was chosen close enough to the "central" terminal. On the occasions where multiple radar coverage was possible, all available radar pictures were used in the study. Despite the differences in both scale and coordinate systems, the radar data presentation allows relatively easy comparison among the satellite analyses and other arrays. An alternate approach, manual transformation of the apparent echoes to a latitude-longitude base, would introduce undue subjectiveness into the pilot study.

All other meteorological variables used were transformed to a map base identical with the satellite data contour maps. Analyses included ceiling height (or cloud height where no ceiling exists), visibility, and surface pressure. The ceiling analyses show the amount of cloud cover (C = clear, \( \phi \) = scattered, B = broken, \( \Theta \) = overcast, O = obscured). Visibility analyses also indicate significant weather at each station (see Appendix B). Examples of these analyses are given in the following sections. The choice of those noted occurred because both ceiling and visibility are special quantities of interest at air terminals; whereas, surface pressure, radar echoes, and satellite observations of cloudiness are considered to be potential predictors of the desired parameters.
3.0 Simultaneous Analysis

In this first part of the pilot study we present simultaneous analyses of the ATS-III spin scan camera measurements and specific conventional meteorological observations over the same regions about a central station. In order to depict the weather situation over a region of 100 mile radius the analyses are presented for rectangular latitude-longitude areas (4° x 5°); slightly larger areas than required. As mentioned earlier the central stations are not necessarily at the geometric center of the analyses.

3.0 Selected Displays

A total of 51 (17 picture times x 3 station cases/picture time) joint analyses of the satellite and conventional data have been completed. Only selected cases will be shown in this section; the remainder are available for study on special request. The three chosen examples differ only in small ways from the remaining 6 station cases.

The examples (see Appendix C) include (a) a single time sample with multiple radar coverage over a region of sharp cloud gradients and extensive thunderstorm activity on April 19, 1968; (b) a contrast between fair and severe weather conditions at a terminal over a short interval of time on April 23, 1968; and (c) an extended time series of simultaneous observations from the satellite and the ground on April 4, 1969.

Detailed interpretation of the concurrent analyses is left to the reader who may have special objectives in examining the data set of this pilot study. A few comments are warranted of course, but the authors welcome post-publication discussion with all interested parties.

3.1.1 April 19, 1968; Witchita Falls, Texas (SPS)

Figures 7-12 depict the visibility, ceiling, radar and ATS satellite data analyses for the Witchita Falls, Texas area at 2318 GMT (1718 local time). Radar coverage is excellent from three sites: Oklahoma City, Fort Worth and Witchita. The ceiling and visibility reports comple-
ment the satellite view to show a wedge of clearing behind an active cold front. Radar echoes show strong squall line activity throughout eastern Oklahoma and south along the 97th meridian to below Ft. Worth. Consistent echo reports are also found in the vicinity of Hobart, Oklahoma. Reflected radiance measurements from the ATS-III show both the general cloud pattern as well as the very brightest regions and sharp gradients that indicate extensive cloud thickness. These latter agree very well with the simultaneous radar reports.

3.1.2 April 23, 1968; Columbus, Ohio (CMH)

The most important aspect of the geosynchronous satellite data is the ability to view a region (i.e., an air terminal) at high areal resolution nearly continuously in time. Between 1701 and 1946 GMT the Columbus, Ohio region experienced a high contrast in weather conditions with rapid development and advection of the active region seen just south of the vortex center in Figures 2a,b and c. The meteorological data in figures 13-18 show this sudden change very well. Satellite data analyses for the two time (figures 19a and 19b) also mark very well, perhaps even better, the movement and development of the bright triangular cloud mass and its neighboring regions of deep convection. Once again agreement between satellite and radar reports is quite good. How well was radar used as a forecast tool in this situation? In the absence of radar, could the nearly continuous satellite observations of reflected energy have been used in a prognostic technique? These questions suggest further study. It is evident, however, that the satellite measurements (giving total areal coverage over the region of interest) could improve the ceiling and visibility analyses derived from a few discrete points over the area. Despite the apparent complementary value of the satellite data, none of the conventional data analyses in this report were modified in this way.

3.1.3 April 4, 1969; Dodge City, Kansas (DDC)

At 8 a.m. local time a relatively weak surface low was centered in the region of the Dodge City terminal.
From about 8:30 a.m. until nearly 2 p.m. the ATS-III spinscan camera experiment acquired eight high-quality taped views of this region. Thus, the case gives us an opportunity to display a long time series of simultaneous satellite and conventional data. Figures 20-28 give the radiance fields and radar reports (from Wichita). Note that as the radar echoes subside during 1600-1800 GMT, the ATS radiation analyses show a temporary lack of very bright regions and a lessening of brightness gradients.

Surface pressure reports (figure 29-36) show smooth patterns of eastward movement and gradual weakening of the surface low. A glance at the following sequence of ceiling and visibility maps (Figures 37-52) shows that the smooth pressure field does not well depict the real-time weather over the area of study. Indeed the visibility and ceiling at Dodge City are generally decreasing as the pressure rises. Obviously the air flows now completely encircling the filling low are influencing the terminal weather.

3.2 Time Series

The Dodge City case from April 4, 1969 is an example of a relatively long viewing period from the geosynchronous satellite. Thus it provides the opportunity to study a time cross section of the parameters considered in this study (figure 53). The slow pressure rise already mentioned is apparent over the 6 hour interval. Ceiling and visibility reports were consistent for 5 hours at 15 miles and unlimited, no radar echoes were reported within 15 miles of the station.

Between 1900 and 2000 GMT station weather increases rapidly. A simultaneous 100% change of brightness occurs. Scanning the satellite data analyses we see that the gradient making the major cloud boundary was moving east-southeast at about 20 mph and could have been forecast for Dodge City.

But why the apparently anomalous brightness change of nearly equal magnitude that occurs nearly two hours earlier? Since this is near local noon a large specular reflection component not completely accounted for in the brightness normalization scheme is immediately suspect.
This problem can be treated further using results in the next section where other descriptions of the radiance pattern in addition to the simple field values, are considered.

Since Dodge City was quite free of significant weather during the time series (it had consistently high visibilities for the region studied) it serves as a good example of the advection monitoring capability of the geosynchronous satellite data. However, Hill City, Kansas, about 110 miles directly north, reported thunderstorms and rain showers, especially early in the day. A parameter cross section for this location is shown in figure 54. Here the situation is more chaotic with radar echoes near the station early in the day. Despite the probably heterogeneous cloud conditions (which might impair interpretation of the satellite data as well as make the surface observations difficult) we still note a relative agreement between the satellite observations and changing terminal weather (the brightness increase at 1130 local time is seen here also, but to a lesser magnitude).

To aid further study of a prime attribute of the ATS data, namely its frequent views of the same region, several additional time series are shown in figures 55-60. They were chosen to illustrate particularly low ceiling and visibility conditions. In these cases, it is especially interesting to compare surface pressure tendency, radar events and satellite measurements with sky cover and visibility reports.
4.0 Statistics of Reflected Radiance Fields

A second portion of the pilot study involved experimentation with the ordering of various statistical characteristics of the satellite data field onto a fixed grid (NMC). This was done for all the central station cases noted in the earlier section (thus 51 such arrays are available). Again, however, only some selected examples are included in this report.

The NMC (National Meteorological Center) grid is a regular square mesh overlaying a polar stereographic projection (true at 60°N). One NMC grid square over the central U.S. (35-40°N) is about 200 miles on a side. We ordered the radiance statistics into a 7 x 7 matrix of 1/16 NMC grids (approx. 50 x 50 miles), thus considering a region of about 350 miles square around the central stations.

Figures 61-71 depict eleven sample arrays of satellite data statistics. They include: a) mean brightness of the grid mesh $\overline{B}_{ij}$
b) standard deviation of brightness $\sigma_B$
c) relative dispersion $\sigma_B/\overline{B}_{ij}$
d) departure of mean grid brightness from the field mean $\overline{B} - \overline{B}_{ij}$, and
e) change of brightness from one grid time to the next grid time $\Delta\overline{B}_{ij}$

A typical grid mesh contained 30,400 measurements at full camera resolution; all of these were used to derive the statistics.

No analysis of the statistical fields was attempted; the reader may scan the arrays or analyses as he wishes. Of course several other descriptions of the field could have been chosen, but the most simple were thought best for this first attempt. They show, collectively, that the ATS data present a wide dynamic range and regularly varying, yet discontinuous, field of observations. Such a quantitative repre-

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5 In the data processing for the arrays every two digital elements were averaged. (Since the sampling rate for digitization is about twice the frequency of contiguous scan spots, we retain geometrical resolution).
sentation of the cloud field offers many further research possibilities.
5.0 Summary of the Pilot Study

This study contains no conclusions; rather it poses questions and allows evaluation and planning of future work. It contains examples of the data set that has been assembled, the first extensive use of quantitative geosynchronous satellite measurements with concurrent conventional meteorological observation on a high resolution space and time scale.

In the opinion of the authors it shows that it should be profitable to proceed to a test of the use of quantitative radiance measurements from geosynchronous satellites in very short range terminal forecast techniques. This opinion is based on the apparently good representation of both homogeneous cloud masses and regions of intensive cloud development by the reflected radiance measurements from ATS-III. As can be seen from the time series, changes in radiance measured from a geosynchronous satellite are not always representative of changes in reported station ceiling and visibility. Thus, further study with the satellite data should emphasize other forecast parameters as well.

During the course of this study, lack of an internal relative calibration check in the ATS-III spinscan camera system prevented easy intercomparison of radiance measurements obtained on different days. While this problem can be overcome by extracting special information from the image scene (as is done for data mapping), future satellite systems should include an internal reference.
6.0 Acknowledgements

This study was directed by Dr. Thomas Vonder Haar, Principal investigator, with Richard Cram as project manager. Miss Sharon Nicholson assisted with the data analysis and Eric Smith and Ralph DeDecker coded the programs to use the geosynchronous satellite data. Professors Verner Suomi and Robert Parent were principal investigators for the mult-color spinscan camera experiment on NASA's ATS-III spacecraft. We thank all who aided with the design and data acquisition phases of the experiment.
7.0 References


8.0 List of Figures

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<th>Figure</th>
<th>Description</th>
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</tr>
<tr>
<td>1b</td>
<td>Close-up of US for 19 April 1968</td>
</tr>
<tr>
<td>1c</td>
<td>Area of ATS tape normalization</td>
</tr>
<tr>
<td>2a</td>
<td>Same for 23 April 1968</td>
</tr>
<tr>
<td>2b</td>
<td>Same for 23 April 1968</td>
</tr>
<tr>
<td>2c</td>
<td>Same for 23 April 1968</td>
</tr>
<tr>
<td>3a</td>
<td>Same for 4 April 1969</td>
</tr>
<tr>
<td>3b</td>
<td>Same for 4 April 1969</td>
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<tr>
<td>3c</td>
<td>Same for 4 April 1969</td>
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<tr>
<td>4a</td>
<td>ESSA Daily weather map for US on morning of 19 April 1968</td>
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<tr>
<td>4b</td>
<td>Same for 23 April 1968</td>
</tr>
<tr>
<td>4c</td>
<td>Same for 4 April 1969</td>
</tr>
<tr>
<td>5</td>
<td>Display of 9 regions selected for study</td>
</tr>
<tr>
<td>6</td>
<td>Example of radar coverage over Columbus, Ohio case study by the Cincinnati, Ohio radar</td>
</tr>
<tr>
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</tbody>
</table>
Appendix A

Bi-directional Radiance Normalization Method
(developed under separate contract)

The reflected solar radiance from clouds depends to a large extent on four variables: (a) drop size distribution and phase state (b) liquid water content (c) cloud thickness and (d) angular condition of the measurement scene (zenith angles of sun and sensor $(\zeta, \theta)$ and their relative azimuth $(\phi)$). The first three variables depend on the physical characteristics of the cloud; the angular dependence is more related to the conditions of measurement and adds unwanted "noise".

If clouds, or other natural surfaces, were known to reflect solar energy according to Lamberts law (i.e., appeared as isotropic reflectors when viewed from different angles by an instrument of fixed field-of-view), then all angular dependence in the magnitude of a radiance measurement could be removed quite easily if one knew the magnitude of incident radiation on the surface of measurement. Given

$$N_r(\theta, \phi) = \int_0^\theta \int_0^{\pi/2} \rho(\zeta, \theta, \phi) N_i \cos \zeta \, d\Omega_i$$

with $N_i$ and $N_r$ the incident and reflected radiance respectively, $\Omega_i$ the total solid angle subtended by the radiation source at the reflecting surface and $\rho$, the bi-directional reflectance (a property of the surface with units sr$^{-1}$). For a Lambert surface, the total directional reflectance $r$ equals $\pi \rho$ since $\rho$ = constant $\cdot$ cos $\theta$. This follows from:

$$r(\zeta) = \int_0^{2\pi} \int_0^{\pi/2} \rho(\zeta, \theta, \phi) \cos \theta \sin \theta \, d\theta \, d\phi$$

for a non-lambert reflector we must be able to specify the angular dependence of $\rho$ in some similar manner in order to (numerically) integrate (2).

From special aircraft observation of cloud reflectives (Brennen and Bandeen (5) and others), as well as available theoretical calculations Raschke and Bandeen (6) have assembled information suitable to empirically represent $\rho(\zeta, \theta, \phi)$. They do this in terms of a factor

$$x(\zeta, \theta, \phi) = \frac{r(\zeta)}{\pi \rho}$$

with $x > 1$ indicating reflected radiance greater than
that which would be received from a Lambert reflector when viewed under
the same angular conditions \((\zeta, \theta, \phi)\); vice versa for \(\chi (\zeta, \theta, \phi) < 1\). (i.e.,
large \(\chi\) values represent strong forward scattering properties that are
unique to many atmosphere constituents including water droplets).

In practice, a time sequence of measurements of a given surface,
cloud or land may be taken under different angular conditions because
of:

(a) rapid movement of the instrument (i.e., on a satellite or
aircraft) thus changing \(\theta\) and/or \(\phi\) while \(\zeta = \zeta(t) \times\) constant,
or
(b) relatively long elapsed time interval from beginning to
end of the sequence (i.e., sensor mounted on a fixed plat-
form) thus changing \(\zeta(t)\) and \(\phi\) with \(\theta = \) constant.

For either case, the relative comparison of measurements within the
sequence requires the ability to normalize for angular dependence of
the reflected radiation.

Vonder Haar (3) discusses the proportionality between relative
radiance measurements, \(D\) (called also, digital counts or brightness
values) and the bi-directional reflectance, \(p\) (i.e., \(D = \frac{V_C}{\lambda p}\)). If
the physical characteristics of a cloud remain absolutely constant,
but it is viewed under different angular conditions, it will have dif-
ferent values of \(p\) and therefore \(D\). However, if \(p\) is scaled by a
proper factor (say \(\chi(\zeta, \theta, \phi)\)) it can be effectively normalized to a
common base (in this case to the total effective "diffuse" reflec-
tance that would arise from a Lambert reflector). After further
weighting by any change in magnitude of incident solar irradiance
arising from the change in angular conditions we convert from diffuse
reflectance to \(p\) using a new, appropriate \(\chi\) value and thus to a new
value of \(D\). The new value is that which would be output from the
ATS spinscan system if a cloud that did not change physical character
was viewed at a different time (similar logic applies to views of
identical clouds viewed at the same time but at widely separated
geographical locations).
This bi-directional radiance normalization technique was used in the present report as indicated. It is the best available today but needs continuous revision as more data of the kind described in (5) become available.
Appendix B

Code for Ceiling & Visibility Analyses

Symbols

Clouds & Ceiling:

Q or c = clear

= scattered

= broken

= overcast

= obscure

There is technically no ceiling if the sky is scattered or clear (i.e., less than .6 sky cover)

- before a symbol means thin; 1/2 or more of the sky is transparent

Cirriform cloud height is not estimated and is not called a ceiling.

/ = cirriform \< .6 sky cover

U = cirriform \> .6 sky cover

Ex: 12 = 1200 ft., broken; /- = thin, cirriform

Weather:

R = rain

L = drizzle

Z = freezing

D = dust

T = thunderstorm

(with no rain associated)

W = shower

E = sleet

B = blowing

F = fog

H = haze

K = smoke

S = snow

A = hail

GF = ground fog

+ = heavy

++ = very heavy

- = light

-- = very light
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C = Central Time = G.M.T. - 6 hrs.
E = Eastern Time = G.M.T. - 5 hrs.
M = Mountain Time = G.M.T. - 7 hrs.
COLUMBUS, OHIO
APR. 23, 68

VISIBILITY

≈ 1946 Z

Figure 16
DODGE CITY, KAN.  APR. 4, 69
PRESSURE (M.S.L.)  ≈ 1556 Z

Figure 31
DODGE CITY, KAN. APR. 4, 69
PRESSURE (M.S.L.) ≈ 1648 Z

Figure 32
DODGE CITY, KAN.    APR. 4, 69
CEILING    $\approx 1739 \text{Z}$
DODGE CITY, KAN.  APR. 4, 69
CEILING  ≈ 1948 Z

Figure 44
DODGE CITY, KAN.  APR. 4, 69

VISIBILITY  ≈ 1739 Z

Figure 40
DODGE CITY, KAN. APR. 4, 69

\[ \text{VISIBILITY} \approx 1805^\circ Z \]
DODGE CITY, KAN. APR. 4, 69

VISIBILITY ≈ 1855 Z
HILL CITY, KANSAS
APRIL 4, 1969

Figure 54
OMAHA, NEB. APRIL 19, 1968

CEILING •••••••
PRESSURE ••••
VISIBILITY X X X
BRIGHTNESS ••••
RAIN △ △ △
RADAR • • •
(WITHIN 15 MILES)
FOG F F F

NOTE:
RADAR & BRIGHTNESS VALUES FOR TIMES 2156-2318 ONLY

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**LAT, LONG + 1/16 NWP GRID**

**TOTAL:**

26.98 .663

17.33 -7.97

**MEAN REL. DIS.**

$\bar{B}_i - \bar{B}_j$

**STD. DEV. $\Delta \bar{B}$**

*Figure 61*
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**Figure 62**
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**LAT, LONG + 1/16 NWP GRID**

**1526 Z**

**TOTAL:**

61.28 .505

30.92 15.02

**MEAN REL. DIS.**

$\bar{B}_T$ - $\bar{B}_{H,1}$

**STD. DEV. $\Delta \bar{B}$**

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**LAT, LONG +**

**1/16 NWP GRID**

**1556 Z**

**TOTAL:**

68.97  .487

33.60  7.69

**MEAN REL. DIS.**

**STD. DEV. ΔB**

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**GARDEN CITY, KAN. (GCK) AP. 4, 69**

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<td>Short Range Forecasting</td>
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<td>Ceiling/Visibility</td>
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<td>Radiation Measurements</td>
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<td>Cloud Observations</td>
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The study assembles a unified body of data consisting of very high space and time resolution reflected radiance measurements from a geosynchronous satellite (ATS-III) along with concurrent meteorological radar, ceiling, visibility and surface pressure reports at selected air terminals in the central United States. This data set allows familiarization with the meteorological potential of nearly continuous observation of cloud conditions from a geosynchronous platform. It may also serve as initial input to quantitative techniques for evaluating the satellite data and/or for testing its usefulness in very short range weather forecasting. In this regard, a second portion of the study presents arrays of statistical descriptors of the satellite data.