

Satellite

USE OF ENHANCED INFRARED SATELLITE IMAGERY FOR SHORT-TERM THUNDERSTORM ADVISORIES TO AVIATION

by

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ABSTRACT

Convective SIGMET's (WST's) are short-term thunderstorm advisories to aviation interests. Currently they are based on radar data. Several ambiguities with radar data make it difficult for the meteorologist to issue effective WST's. Enhanced infrared synchronous satellite data can alleviate many of these problems. The WST radar-oriented criteria are related to satellite images. The storm summit isotherm expansion rate derived from enhanced IR Imagery is shown to be associated with thunderstorm radar reflectivity.

The criterion for WST issuance, 45 dBZ, corresponds to an expansion rate of about one degree square latitude per hour for the first hour of growth. The discussion leads to proposed modifications of the WST criteria that overcome the problems associated with the radar-oriented criteria.

1. INTRODUCTION

Since May, 1978, the National Severe Storms Forecast Center (NSSFC) has been issuing hourly short-term thunderstorm advisories for aviation interests. These convective SIGMET's or WST's for short, are issued for the following phenomena:

1. Tornadoes
2. Lines of thunderstorms
3. Embedded thunderstorms
4. Thunderstorm areas with equivalent radar reflectivity of 45 dBZ and area coverage of 0.4 or greater.
5. Hail greater than or equal to 3/4 inch diameter.

Any WST also implies severe or greater turbulence, severe icing, and low-level wind shear.

Thunderstorms that meet any of these criteria present significant hazards to aviation and can cause problems in flight operations. The fourth criterion is based on a study by Burnham and Lee (2) which showed that storms whose maximum radar reflectivity is 45 dBZ or greater have a high probability of being associated with severe turbulence. While many storms reach this reflectivity sometime in their lives, most remain quite small and are easily circumnavigable. Therefore, criterion 4 is for those thunderstorm clusters either through which aircraft would find difficult to navigate or are impenetrable.

Radar data are the main information used by the meteorologist responsible for the WST. At the radar site, reflectivity is processed by a Digital Video

Integrator Processor (DVIP) according to a scheme shown in Figure 1. A reflectivity of 45 dBZ is the beginning of DVIP level 4. Once an hour the observed echoes on the PPI scope are manually mapped onto a grid of squares approximately 41 km on a side. The maximum DVIP level within each grid square is reported. A meteorological technician at NSSFC plots these Manually Digitized Radar (MDR) data each hour. The meteorologist charged with issuing WST's determines whether a particular complex of thunderstorms meets one of the issuance criteria. If it does, a message outlining the system and forecasting what the system will do during the next two hours is composed and transmitted.

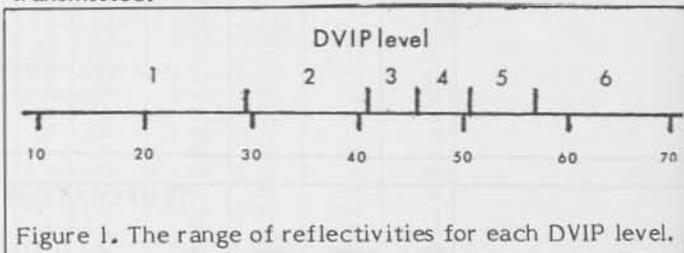


Figure 1. The range of reflectivities for each DVIP level.

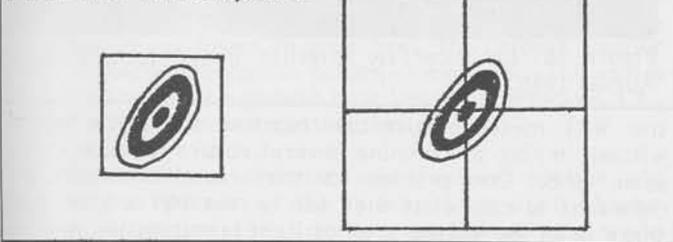
While the WST Meteorologist uses other data, such as surface synoptic and satellite data, to aid in formulating WST's, in the final analysis, the criteria for WST's are radar-oriented. This paper discusses the problems of relying on radar compounded by the observation system of MDR squares. Synchronous satellite data, especially enhanced infrared data, can help alleviate these problems. While satellite detection of significant thunderstorms has problems of its own, many of these can be overcome by careful analysis of the images. Rules for overcoming these shortcomings are presented leading to proposed modifications of the radar-oriented criteria for issuing WST's.

2. THE PROBLEMS WITH RADAR

Over the past 40 years or so radar has proliferated to a point where it now is the primary tool for monitoring thunderstorms. Radar observations are taken every hour in a network that presently contains 80 stations across the U.S. As mentioned above, the observations are coded in MDR grid squares before transmission. The MDR grid is too crude to accurately locate significant thunderstorms and to ascertain areal coverage. For example, a "level 4" thunderstorm echo that would fit inside one MDR square is reported as being four times larger when it is at the junction of 4 MDR squares (Figure 2). This is because the observing rules require the observer to encode the maximum reflectivity level in each square regardless of its location within the square. An example of this occurred in the observation over

eastern Colorado shown in Figure 3. The MDR data suggest a very large thunderstorm complex while the enhanced IR satellite image shows only two very small storms. Because of the "broad-brush" approach, the MDR data grossly misrepresented the actual thunderstorm situation in eastern Colorado. This problem should be resolved upon the implementation by the National Weather Service of the RADEP program in which automatically digitized data over a grid on the order of 6 KM squares is transmitted. Digesting the nearly fiftyfold increase in data points in the short time period allowed between the radar observation time and the WST issuance time (presently 20 minutes) will pose another kind of a problem for the WST meteorologist.

Figure 2. How a small "level 4" storm increases its size in the MDR observation system when located at the junction of 4 MDR squares.



Even if "live" radar data were available to the WST meteorologist, and there were efficient ways to digest them, there still are inherent problems in the radar hardware itself that can make the data ambiguous. One hardware problem is with the DVIP. The DVIP level displayed by the radar at any "point" on the PPI is actually an average of all the reflectivities within a small volume between two range arcs as shown in Figure 4. Because this volume is much smaller at short range than at long range, a spurious peak in radar return will not be averaged out at the short range, and a DVIP level one higher often results. Since WST's are DVIP level sensitive, this can cause a needless WST issuance for an area of thunderstorms near a station.

Poorly calibrated radars present a more serious problem. Ideally, all radars in the observation network would be calibrated identically. In reality this is not the case. There are certain radars that have a reputation at NSSFC for being consistently "hot" or consistently "cold". Meteorologists at NSSFC have brought this problem to the attention of the observing stations in question directly on a case-by-case basis with minimal success. Increased quality control will solve the problem, but in the meantime, the WST meteorologist will always have doubt as to the true DVIP levels.

Even if this calibration problem did not exist, there is still a fundamental problem in that radar detects only the precipitating part of the thunderstorm. All the visible cloud is not collocated with the radar echo. Lewis (3) recommends that aircraft remain over 5 nautical miles away from any strong radar echoes. Further, it is on the edges of the cumulonimbi that severe turbulence is likely to be encountered (2). Gust fronts formed by some thunderstorms can move away from the radar echo (4). A gust front of this type may cause significant unexpected low-level wind shear.

There are other problems of a lesser nature such as attenuation, beam ducting, ground clutter, and bright-band reflectivity, that occasionally cause a radar to perceive wrongly what is really occurring. All of

these problems, especially the calibration problem, make reliance on radar observations for WST issuance very difficult. Criteria not based solely on radar are needed. This is where synchronous satellite data can help.

3. USE OF SATELLITE DATA TO IDENTIFY SIGNIFICANT THUNDERSTORMS

Synchronous satellite images give meteorologists a complete view of a thunderstorm complex rather than the piecemeal portions given by radar. The meteorologist can also observe how thunderstorms are interacting with the environmental flow. Since there is only one satellite, rather than a network of radars, storm movement is easier to compute. Also, the calibration is constant over the entire field in view. In addition, the satellite views more of the cumulonimbus cloud. It can spot features of significance to aircraft operations where radar cannot. Throughout the region shown in Figure 3 differences are apparent in the radar and satellite representations. The storms in west Texas are larger and appear more of a flight hazard than storms in Kansas or Colorado, yet the radar shows the opposite.

It should be understood that satellite data also have problems of their own. One problem is missing data. If a radar goes out, there is usually a back-up radar in the vicinity that can take over and transmit observations. With geostationary satellites there are no collocated satellites that can be turned on when the primary system goes down. There are two operational satellites observing the United States, one from the east and one from the west. When one goes out usually the other is still working. However, the change in perspective is a problem in maintaining continuity, and it is difficult to see detail in the coastal areas opposite the satellite. Fortunately, satellite outage is rare. Another problem is misgridded data. This can be overcome by manually placing a grid over the image using known geographical locations on the image such as lakes, bays, peninsulas, etc. When the image is gridded properly, there is still a problem of accurately locating thunderstorms on the image because of viewing angle. For the GOES-East images, storm tops appear north and west of where they really are (5). For a 13 km (40,000 ft) high storm, a southeastward correction of about 8 km (5 nm) should be made at 30N and 16 km (10 nm) at 45N.

Perhaps the most important problem is interpretation of the data. Research on thunderstorms using satellite imagery has only begun recently. Some of the features on visual images associated with thunderstorms have been discussed by Purdom (6,7) and Anderson (8). However, enhanced infrared imagery has been shown to be more useful in monitoring thunderstorm growth patterns, which, in turn, have been shown to be very useful in interpreting thunderstorm strength. Scofield and Oliver (9) correlated growth rates with rainfall rates. Adler and Fenn (10,11) have shown the importance of cloud top growth rate and minimum cloud top temperature. McCann (12) examined the "enhanced-V" signature on the enhanced IR images and showed that this signature indicated the likelihood of a severe thunderstorm. Maddox (13) discussed very large thunderstorm complexes and the associated weather conditions. These research studies can be used to relate the satellite imagery to each of the radar-oriented criteria.

a. Severe Thunderstorms

Tornadoes and large hail are better lumped together because satellite images do not distinguish between the two. Perhaps the best satellite indicator of severe storms is the "enhanced-V" signature discussed by McCann (12). When this signature (Figure 5) is indicated on an enhanced IR picture, there is a high probability of severe weather occurring within one hour afterward. (McCann's study estimates this probability near 70 percent.) There are two rules for identification of enhanced-V's. First, the enhanced-V must be associated with a growing thunderstorm. By "growing" it is meant that the coldest IR temperature contours are expanding or the minimum top temperature is decreasing. Second, once a storm has established an enhanced-V, it should be considered severe as long as it continues to grow using the same definition of growth above.

Adler and Fenn (10,11) also showed that a rapid growth rate of the coldest IR isotherms is also a good indicator of severe storms. Their study was limited to a few severe days and no reliable threshold was given. However, any storm whose anvil grows very fast can be a severe storm. They did point out that new thunderstorms occasionally form under a cirrus shield, and so growth rate early in the storm's life will not be observed. This is a minor problem because the storm is usually very small until it penetrates the cirrus.

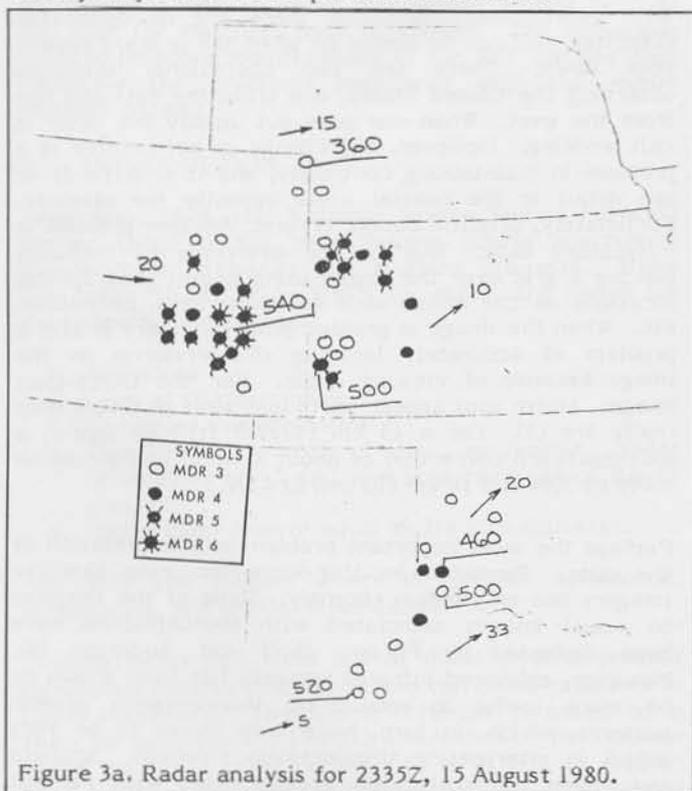


Figure 3a. Radar analysis for 2335Z, 15 August 1980.

b. Lines of Thunderstorms

An informal survey of meteorologists at Center Weather Service Units (CWSU) at Air Route Traffic Control Centers (ARTCC) showed that thunderstorms in lines cause the most problems in air traffic control. This is because they usually affect a large number of jet routes, and deviation of aircraft around these lines (if impenetrable) causes the traffic to bunch up in one area and creates a collision problem. With satellite imagery,

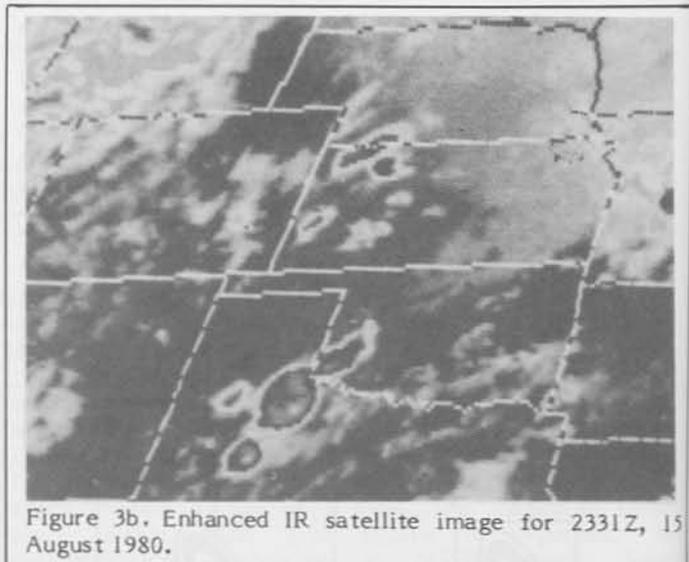


Figure 3b. Enhanced IR satellite image for 2331Z, 15 August 1980.

the WST meteorologist can monitor the line's extent without trying to combine several radars looking at the same line. One problem is that radar observers are reluctant to call what they see on the PPI a line when there is an associated area of light precipitation nearby. Figure 6 is an example of such a case. The radar observers reported an area when clearly the satellite picture showed the significant storms lining up.

c. Embedded Thunderstorms

Embedded thunderstorms are a hazard to aviation not only because of the turbulence with them but also because they cannot be seen. Embedded thunderstorms usually occur in areas of widespread rain and many times are difficult to observe on radar because the intensity of the rain may be as strong as the thunderstorms. On enhanced IR satellite images the thunderstorm tops are usually easily picked out among the lower tops. However, caution must be exercised when high tops are observed on satellite images in areas of widespread precipitation. Many times the precipitation area is associated with a comma-shaped cloud associated with a mid-level vorticity center. In those cases there is a substantial high cirrus deck above the rain area which can appear as thunderstorms on the enhanced imagery.

d. Thunderstorm Areas

Another problem often mentioned in the CWSU survey is large thunderstorm clusters. These cause the same kind of route deviation problems as lines, and, on occasion, may affect areas much larger than lines (13).

Radar reflectivity may be related to rainfall rates. Using an equation given by Marshall and Palmer (14),

$$Z = 10 \log (200R)^{1.6}$$

where Z is radar reflectivity (dBZ) and R is rainfall rate (mm hr⁻¹), the rainfall rate associated with a reflectivity of 45 dBZ (the WST criterion) is about 25 mm hr⁻¹ or about 1 inch hr⁻¹.

Scofield and Oliver (9) developed a method for estimating rainfall from the enhanced IR imagery. The rainfall estimation scheme involves measuring the

expansion rate of the coldest isotherm contours on the enhanced IR pictures of a storm to find the rainfall rate. Such estimated rainfall rates are a function of the equilibrium temperature (15). (The tropopause temperature many times is a good approximation.) An IR temperature contour about 5C warmer than the equilibrium temperature is usually representative of the coldest portion of the storm's anvil during the first part of growth. An expansion rate of this contour of 15,000 km² hr⁻¹ during the first hour after the contour is initially observed corresponds to a rainfall rate of 1 inch hr⁻¹ or reflectivity of 45 dBZ. Putting this rate in easily measured terms, this contour would be slightly larger than one degree latitude square after the first hour of growth. Therefore, any storm which expands at this rate would meet the radar WST criterion. Rainfall estimation by measuring this contour after the first hour becomes more complicated. In order to simplify the procedure, it can be assumed that 45 dBZ persists as long as the storm continues to grow, i.e., the coldest contour in the IR picture becomes colder or expands. The storm diminishes when the growth rate becomes negative, i.e., top warming or contour contraction.

Scofield and Oliver discussed the "active" portion and the "inactive" portion of the thunderstorm anvil. Under the active portion the heaviest rainfall occurs, while under the inactive portion there is little or no rainfall. The IR temperature contour defined above corresponds well to the active portion of the Cb. Furthermore, Maddox (13) showed that precipitation is usually falling under this portion. Therefore, the contour defined above will be called the "active contour".

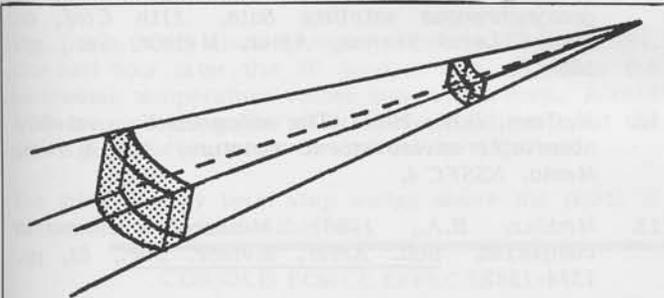


Figure 4. Exaggerated sector of a DVIP showing a much smaller volume at near range being integrated than at far range.

The most likely portion of the storm to have severe turbulence is the area within the active contour; therefore, in general, the active contour defines an area appropriate for a WST. This opinion is also shared by many CWSU meteorologists. Pilots do not wish to fly into the anvil of a storm near the updraft because hail and severe turbulence are common. In the inactive anvil portion away from the central core of the Cb, typically only light to moderate turbulence is encountered.

Storms whose active contour area reaches one degree latitude square are very large thunderstorms compared to normal size thunderstorms seen on satellite images. It is these storms that cause the most route deviation headaches for ARTCC's. Smaller closely-spaced thunderstorms also cause problems because of the difficulty navigating through the area. Therefore, a rule for WST issuance could be to always issue one for growing storm complexes whose active contour areas are one degree square or larger.

Storms that are known to have produced strong wind gusts sometimes remain an aviation hazard long after the satellite image shows top decrease. The gust front that the storm produces sometimes is so strong that it remains intact hours after the storm's updraft weakens. Case studies were done by McCann (4) and Fujita (5). Since the gust front produces significant low-level wind shear, a WST should be considered for all storms known to have produced a wind gust greater than 17 m sec⁻¹ (35 knots), regardless of the size or growth rate shown by satellite, for two hours after the last known strong wind gust. The active contour should still define the area. It should be noted that radar also detects this type of storm poorly. The bow echo that has been noted with some of these storms (5) occurs after the gust front has reached its peak intensity. However, many of these storms fail to even show the bow echo signature on radar.



Figure 5. Enhanced IR satellite image for 2343Z, 10 April 1979. An enhanced-V (white arrow) is indicated for the storm that eventually produced the Wichita Falls TX tornado.

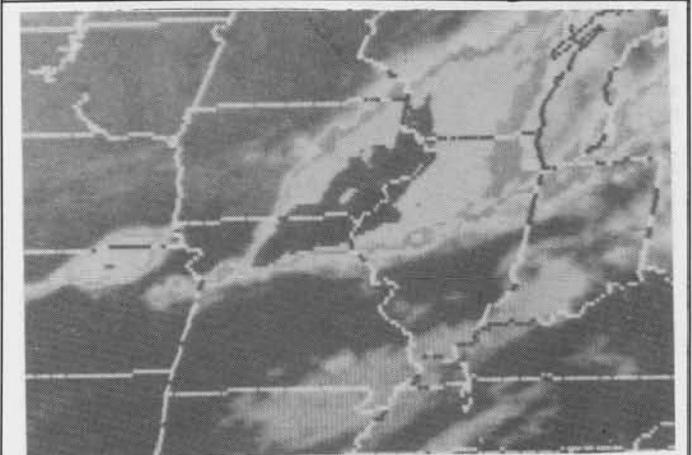


Figure 6. Enhanced IR satellite image for 1130Z, 4 September 1980, showing how the satellite detects a line of thunderstorms not observed as such by the radar network.

