THE INTEGRATED TERMINAL WEATHER SYSTEM (ITWS) STORM CELL INFORMATION AND WEATHER IMPACTED AIRSPACE DETECTION ALGORITHM*

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1. INTRODUCTION

The Integrated Terminal Weather System (ITWS) is an FAA–sponsored program (Sankey, 1993; Ducot, 1993) whose objective is to acquire data and products from a variety of weather sensors, integrate the data and create aviation weather products for users, such as Air Traffic (AT) controllers and traffic managers, pilots, and airline and airport operations managers. The goal of ITWS is to increase capacity at airports, reduce controller workload, and enhance safety.

The objective of the ITWS Storm Cell Information (StoCel) and Weather Impacted Airspace (WIA) Detection products is to identify storm cell characteristics (echo top, echo bottom, presence of heavy rain, hail, etc.) and airspace that pilots are likely to avoid because it contains hazardous weather. The StoCel/WIA products rely on the integration of pencil–beam data and products and Air Surveillance Radar (ASR–9) Weather Channel data. ASR–9 radars are useful because they cover the entire airspace of interest, perform a volume update at roughly 30–second intervals, and will be the weather representation most widely available to the Air Traffic Control (ATC) community. On the other hand, the ASR–9 has a 4.8° fan beam which results in a vertical integration over the depth of a storm, so information on the vertical structure of storms is lost. In addition, the current ASR–9 Weather Channel may produce false weather regions during ducting or anomalous propagation (AP) conditions. Nearby WSR–88D radars also cover the entire airspace of interest and provide indications of storm vertical structure. However, the volume update rate is typically on the order of 5 to 10 minutes, depending on the scanning strategy. TDWR radars perform volume updates about every 2.5 to 3 minutes, but perform sector scans that do not cover the entire airspace. Integration of the data from these various sensors produces a product that is superior to a product based on any single sensor.

Field tests of components of this algorithm were conducted at Dallas–Ft. Worth (DFW) and Orlando (MCO) International Airports during the summer of 1993. The objectives of these tests are to evaluate the technical performance of the algorithm and the validate the operational concept. This paper will describe the algorithm, and discuss the operational concept and functional requirements for the product. A summary of the results and experiences of the Summer 1993 field tests, and a preliminary evaluation of the performance of the algorithm based on off–line and real–time tests will be provided at the conference.

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2. OPERATIONAL CONCEPT AND FUNCTIONAL REQUIREMENTS

The way pilots react to weather enroute is fundamentally different than in the terminal area. Enroute, pilots can request changes in altitude and/or horizontal deviations around weather which may allow them to avoid a penetration entirely, In the terminal area where aircraft are concentrated in a smaller volume of airspace, the requirements for aircraft separation limit the options available to pilots for weather avoidance. In order to land the aircraft, a pilot may be forced to penetrate some weather; his choice is penetrating the least hazardous weather.

Weather in the terminal area will typically adversely impact airport acceptance rates. If the weather is located on flight routes, pilots will usually request deviations around it. This increases the amount of time the aircraft is in the air, causing delays. In addition, controller workload is increased because the number of times a controller must deal with each aircraft and the total number of aircraft in the airspace increases. In these situations, controller workload is reduced and safety is enhanced by lowering the airport acceptance rate (AAR; the number of aircraft per hour that can land at an airport), which further increases delays. There will always be some loss of airport capacity when weather impacts operations. The objective of planning products is to recover as much of the lost capacity as possible by helping to optimize route selection and keeping the AAR as high as possible.

The StoCel/WIA products will be provided to the aviation user community (e.g., pilots, air traffic controllers and supervisors, and automated route planning systems). When data–link becomes available, pilots could use the information to increase safety by avoiding hazardous airspace and for route planning. ATC controllers and supervisors could use the information to anticipate pilot requests for deviations around weather and devise routes that avoid the hazardous airspace. By presenting the information to both pilots and controllers, controller–pilot communications would be facilitated and the need for controllers to provide weather information to pilots would be reduced. In addition, automated route planning systems such as Terminal Air Traffic Control Automation (TATCA; reference) need this information to determine suitable aircraft sequencing, spacing, and approach routes.

The philosophy used in the development of the StoCel/WIA products is to keep the probability of false alarms (P_{fa})

low, even at the expense of probability of detection (P_d). Any accurate information that can be provided to air traffic is an improvement over the current method of operation, but any action taken in response to a false alarm potentially results in loss of capacity.

3. ALGORITHM DESCRIPTION

The approach taken for the Initial Operational Capability (IOC) product is primarily one of product integration. Figure 1 outlines the logic of the detection algorithm. Six–level weather data are acquired from weather channels of all available operational Airport Surveillance Radars (ASR–9) within 45 km of the airport reference point and preprocessed to improve data quality. AP is removed from the mosaic by comparison to a composite reflectivity product created from pencil beam data (e.g., Terminal Doppler Weather Radar (TDWR) or Weather Surveillance Radar–88 Doppler (WSR–88D)). This mosaicked, AP–filtered precipitation map is passed to a correlation tracking algorithm (Chornoboy, 1992) for storm motion estimation and to a cell–finding algorithm for cell identification. Detections from other algorithms (e.g., hail, mesocyclone, tornado, microburst, etc.) are ingested and integrated into the product. The determination of WIA regions is based upon the presence of various hazards.

3.1. MOSAIC

The first step in the product generation is the creation of a mosaic of ASR–9 radar data. The need to mosaic is illustrated in Figure 2 (Engholm and Troxel, 1990). The ASR–9 uses two elevation angles; high and low. The high beam is typically offset from the low beam by about 2°. The antenna gain

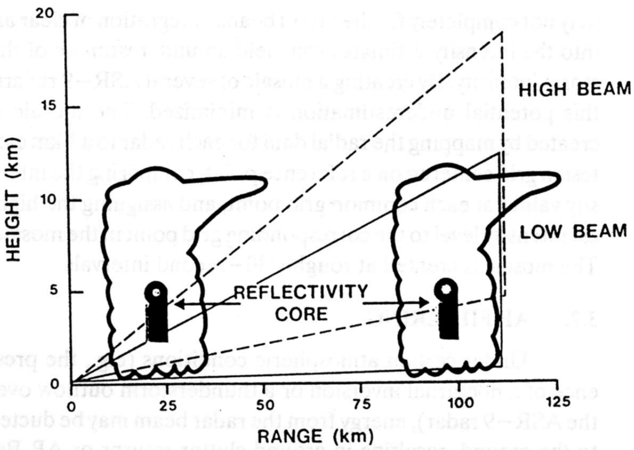

Figure 2. Schematic diagram illustrating the beam filling problem. The –3 dB altitude limits of the ASR–9 antenna pattern are shown for the high (dashed) and low (solid) beam.

varies with elevation such that the radar is most sensitive to precipitation in the lower portion of the beam. The intensity of the weather reported by the ASR–9 weather channel represents a beam–weighted, vertical averaged estimate of storm intensity.

Near the radar (within 30 km), the returns from the high beam are used to reduce ground clutter contamination. At longer ranges, returns from the low beam are used. Weather near the ASR–9 radar (i.e., within the cone of silence) may not be completely sensed by the radar because the radar beam does not contain the entire storm. Therefore, the intensities of storm cells are underestimated. At long ranges, the weather

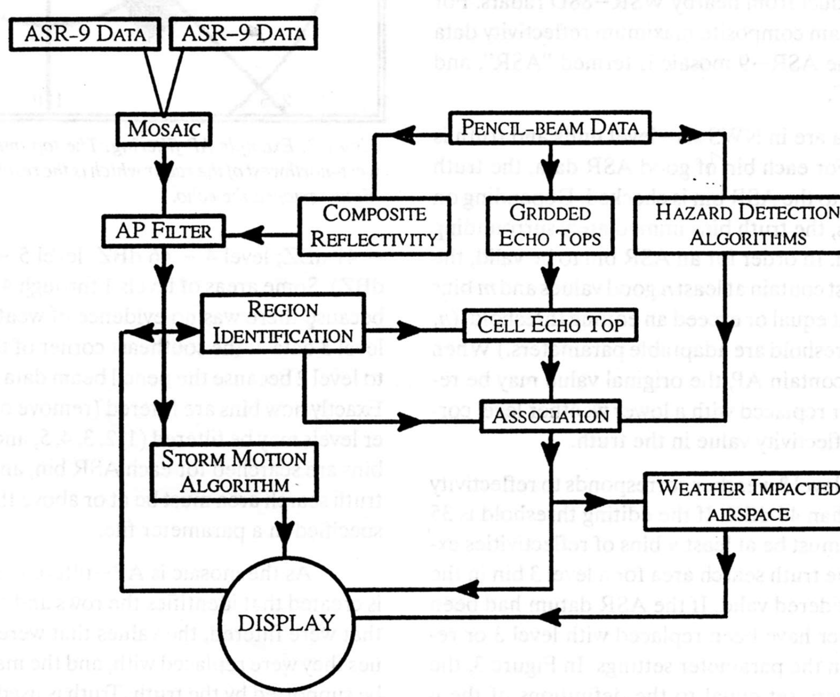

Figure 1. Diagram of ITWS Terminal Storm Information and Weather Impacted Airspace products.

may not completely fill the broad beam. Integration of clear air into the intensity estimates can yield an underestimate of the storm intensity. By creating a mosaic of several ASR−9 radars, this potential underestimation is minimized. The mosaic is created by mapping the radial data for each radar to a 1 km cartesian grid centered on a reference point, comparing the intensity values at each common grid point, and assigning the highest intensity level to the corresponding grid point in the mosaic. The mosaic is created at roughly 30−second intervals.

3.2. AP FILTERING

Under certain atmospheric conditions (e.g., the presence of a nocturnal inversion or a thunderstorm outflow over the ASR−9 radar), energy from the radar beam may be ducted to the ground, resulting in ground clutter returns or AP. Because of the temporal and spatial smoothing that is performed on the raw ASR−9 data, these ground returns become indistinguishable from weather echoes (Figure 3).

Weber et. al (1993) described a method for filtering AP from an ASR−9 radar that was specially configured to detect wind shear. Unfortunately, the signal processing techniques developed for that system cannot be applied to operational ASR−9 radars as they are currently configured. A new AP−filtering technique was developed for the StoCel/WIA algorithm.

The ASR−9 mosaic is compared on a grid point−by−grid point basis to a composite reflectivity product created from pencil beam data. Returns in the ASR−9 mosaic that are are not confirmed by the pencil beam data are assumed to be AP and are filtered from the mosaic. For IOC, the composite reflectivity product will be the 4 km resolution composite maximum reflectivity product from nearby WSR−88D radars. For brevity, the pencil beam composite maximum reflectivity data are called "truth", the ASR−9 mosaic is termed "ASR", and grid points are "bins".

The ASR data are in NWS six−level units and truth is reflectivity in dBZ. For each bin of good ASR data, the truth bin that corresponds to the ASR bin is checked. Depending on the input parameters, the truth bins immediately surrounding may also be searched. In order for an ASR bin to be valid, the truth search area must contain at least *n* good values and *m* bins with reflectivities that equal or exceed an editing threshold. (*n*, *m*, and the editing threshold are adaptable parameters.) When an ASR is found to contain AP, the original value may be removed completely, or replaced with a lower weather level corresponding to the reflectivity value in the truth.

For example, level 3 weather corresponds to reflectivity values of 41 to less than 46 dBZ. If the editing threshold is 35 dBZ, then the there must be at least *n* bins of reflectivities exceeding 35 dBZ in the truth search area for a level 3 bin in the ASR data to be considered valid. If the ASR datum had been level 5, it would either have been replaced with level 3 or removed, depending on the parameter settings. In Figure 3, the editing thresholds were set equal to the definitions of the 6 NWS levels (i.e., level 1 − 18 dBZ; level 2 − 30 dBZ, level 3

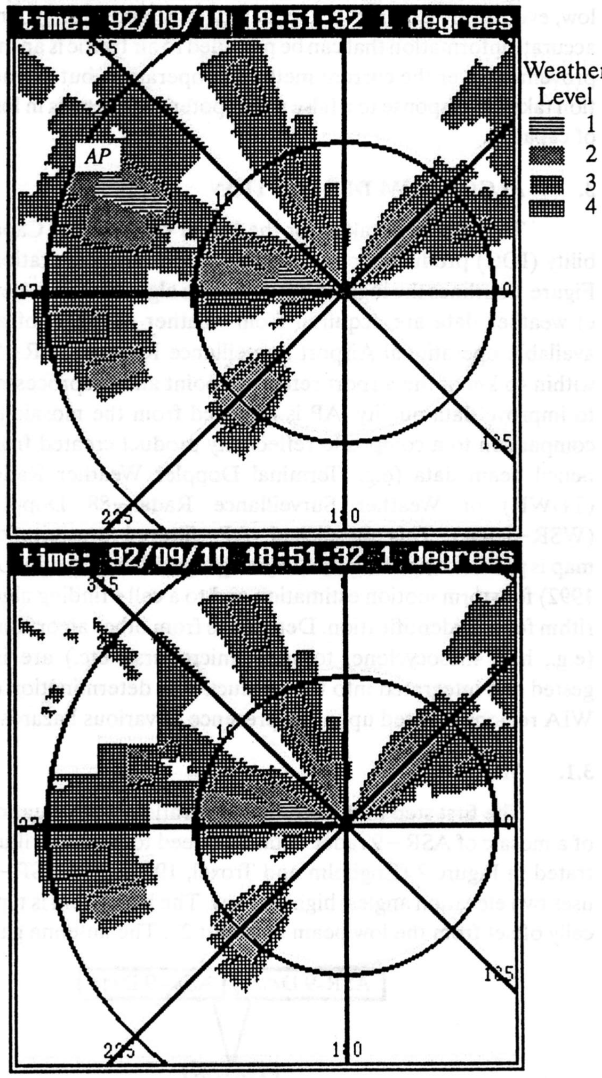

Figure 3. Example AP filtering. The top image shows a level 4 echo west–northwest of the radar which is the result of AP. The filtering technique removed the echo.

− 41 dBZ; level 4 − 46 dBZ, level 5 − 50 dBZ, level 6 − 57 dBZ). Some areas of levels 1 through 4 were removed entirely because there was no evidence of weather in the truth. Some level 3 data at the southeast corner of the storm were reduced to level 2 because the pencil beam data confirmed level 2 data. Exactly how bins are filtered (remove or replace), what weather levels may be filtered (1, 2, 3, 4, 5, and/or 6), how many truth bins are searched for each ASR bin, and how many bins in the truth search area must be at or above the editing threshold are specified in a parameter file.

As the mosaic is AP−filtered, a temporary lookup file is created that identifies the rows and columns of the ASR file that were filtered, the values that were replaced, the new values they were replaced with, and the maximum level that could be supported by the truth. Truth is used only once for filtering. The ASR updates at about 30−second intervals and truth updates about every 6 minutes. ASR data that arrive between the truth updates use the temporary lookup file for filtering. When a temporary file is used to filter ASR data, only the points saved in the temporary file are checked. If an ASR datum is greater than the corresponding maximum in the temporary file, it will be filtered.

Lookup files are used to reduce over–filtering that might occur if the same truth file were used for 6 consecutive minutes. Filtering the same points found to be bad in one file should be safer than using the same truth file for 6 minutes and risk removing weather returns that may have developed after the truth file was created. For example, if a storm develops in a region where weather previously did not exist, it would appear first in the ASR data, which is more up–to–date than the truth data. Comparing the newer ASR data to the older truth data would result in the removal of the newly developed weather as AP. Also, using a lookup file is faster than filtering from a truth file.

The AP–filtered mosaic (or precipitation product) is passed to a correlation tracking algorithm for estimating storm motion.

3.3. CELL FINDING

The next step in the algorithm is cell finding. The 30–second–update precipitation product is passed through a dilation process where regions of heavy rain (an aviation hazard; currently defined as level 5 and greater) are expanded by 1 km (an adaptable parameter). This expansion is used to define a safety buffer zone around heavy rain.

The precipitation data are searched for "segments" or contiguous bins of weather above a threshold. Figure 4 illus-

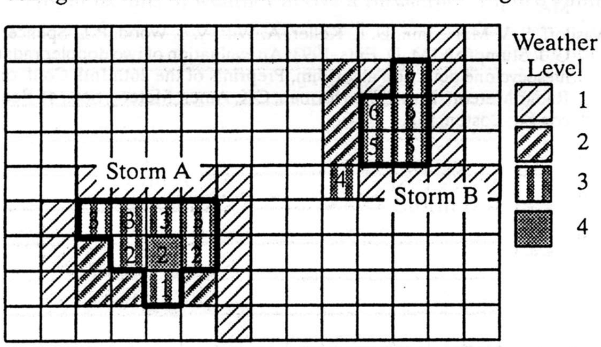

Figure 4. Example of cell finding. The scale for the NWS weather levels is provided at the right. Storm A consists of segments 1, 2, and 3. Storm B consists of segments 5, 6 and 7. Segment 4 does not overlap column–wise with any other segments and therefore is not associated to a cell. (Adapted from Dixon and Wiener, 1994.)

trates the process, which is a adaptation of a technique developed by Dixon and Wiener (1994). A row–wise pass, using a threshold of level 3, is made through the data to build segments. Segments may consist of only one grid point. After all segments are built, the segments are grouped into cells if they segments overlap column–wise. A minimum area threshold (2 km^2) is applied to remove very small cells. Each of the segments in the cell are then searched for the presence of a higher weather level. If a higher level exists, segments are rebuilt and re–associated using the higher threshold. If the area of the cell at the higher weather level does not exceed the minimum area threshold, the cell is defined by the lower threshold. In this way, cells are defined by the highest weather level contained within them whose area exceeds the threshold. The cell shape is defined by a polygon enclosing all of the segments in the cell.

3.4. STORM CELL INFORMATION

The next step in the algorithm is to assign an echo top value to the cells. Bounding boxes are constructed around each of the cells identified in the previous step. A 6–minute–update cartesian echo top product is searched inside the region defined by the bounding boxes and the maximum echo top value (rounded to the nearest 10,000 feet) is assigned to the cell. Each time the cell shapes are generated, echo tops are assigned anew from the available echo top data. It is recognized that storms develop over the 6–minute elapsed time between product updates. However, the vertical resolution of the radar cover at 100 km is about 6000 feet, assuming a 1°–increment scan strategy. In addition, echo tops are reported in flight levels, which are in 10,000 foot increments. Given the coarseness, the change in error in echo top introduced by using a 6–minute–old product is probably not significant.

Additional storm cell information is acquired from a variety of detection algorithms. Although products from any algorithm that identifies storm characteristics can be used, currently the Hail Detection Algorithm (HDA: Witt, 1993), the Mesocyclone Detection Algorithm (MDA; Vasiloff, et. al, 1993), and the Tornado Detection Algorithm (TDA; Vasiloff, 1991) supply detections to the StoCel algorithm. HDA computes a variety of parameters that are used to determine if hail is present in a storm. One of those parameters is the probability of severe hail (POSH), which is the probability that $\geq$ 3/4 inch hail will reach the ground. Although it is believed that hail of any size and at any altitude is of interest to pilots, storm cells are only identified as containing hail if the POSH $\geq$ 50%. The choice of this threshold agrees with the philosophy of maintaining a low P_{fa}. The hail detection is assigned to the nearest ASR cell.

The reported performance of the NSSL mesocyclone and tornado detection algorithms is considered good enough that any detections from these algorithms are ingested into the StoCel product. Because mesocyclones and tornadoes may not be collocated with high reflectivity, the absolute location of mesocyclone and tornado detections are used.

The update rates of these algorithms are a function of the scanning strategy employed. When operating on WSR–88D data, their update rates currently can be as long as 6 minutes. As with echo tops, each time cell shapes are updated, hail detections are associated to the nearest cells. Mesocyclone and tornadoes tracks are available from the respective algorithms, therefore their locations are updated every 30 seconds based on their propagation speeds and directions.

3.5. WEATHER IMPACTED AIRSPACE

As a first approximation, airspace is deemed impacted depending on the presence of weather hazards, specifically heavy rain, hail, tornadoes, and mesocyclones. Heavy rain is defined as level 5 and greater. Any cell containing hail, regardless of the weather level, is flagged as impacted.

Mesocyclones and tornadoes are considered impacted airspaces and are represented by a circular region defined by the point locations of these hazards and a diameter. For tornadoes, the diameter is 6 km. For mesocyclones, the diameter is the diameter of the rotation as detected by the MDA algorithm plus an adaptable threshold (2 km).

4. FUTURE WORK

Preliminary testing of the StoCel/WIA algorithm described above suggests reasonable performance, but a full-blown technical performance appraisal must be conducted using data from a different environments. The algorithm is under development and, at the time of this paper, none of the processes had been tested in real-time with asynchronous data sources. Mosaicking of more than one ASR-9 radar has not been tested because the data are not available. ASR-9 data have been simulated from pencil beam radar data, but the update rates do not mimic real ASR-9 radars.

There are a number of issues involved with the fusion of asynchronous data, which cannot be simulated off-line. For example, ASR-9 radars update at roughly 30-second intervals. Building a mosaic by merging the asynchronous data from these sources is not expected to be difficult since weather does not change significantly in 30 seconds. However, at airports where there is only one ASR-9, it may be desirable or essential to include pencil beam data in the mosaic. Pencil beam data from a single radar may be more than 6 minutes old. Issues involved with merging these data (from single and multiple sources) need to be addressed. Studies need to be conducted to determine how old data can be before it becomes "unusable".

The AP-filtering technique has been tested off-line on a number of cases from Orlando, FL and the results are promising. However, it is expected that some site adaptation and tuning will be needed for the technique to work properly in different locations and in real-time.

tracking of cell shapes is planned, although the method has yet to be decided. Establishing cell tracks would allow a cell to carry its information as it propagates. The current technique of re-associating old detections to new cell shapes may result in assigning the same detection (e.g., hail) to different cells at different times.

Additional hazards can be added to the product as detection algorithms mature. For example, a when a line of cells is impacting an air traffic route, the typical scenario is for pilots to penetrate between cells until a pilot reports that turbulence is too severe and request deviations to find another hole in the line. A turbulence detection algorithm that could accurate identify the location of moderate or greater turbulence relative to the storms could provide guidance to the users. However, such a turbulence detection algorithm does not exist and current algorithms produce so many false alarms as to be useless for planning purposes. Algorithms for detection other storm cell characteristics like "echo bottom", lightning severity, etc. must be identified or developed.

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