

WX1 - AN EXPERT SYSTEM FOR WEATHER RADAR INTERPRETATION

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This paper describes work performed by M.I.T. Lincoln Laboratory for the Federal Aviation Administration to investigate the use of expert system techniques for weather radar interpretation. The design of WX1, a prototype system for recognizing low-altitude wind shear hazards from Doppler weather radar data, is presented. The WX1 system consists of a rule-based expert system coupled to an object-oriented image processing package. Initial results for recognition of two types of low-altitude wind shear are provided.

INTRODUCTION

Low-altitude wind shear has been recognized as a substantial hazard to aircraft, particularly during take-offs and landings [1]. Wind shear is defined as a change in wind speed and direction over some distance; when a large change occurs over a small distance, a wind shear hazard is said to exist. An aircraft encountering wind shear can experience a severe decline in airspeed and lift, resulting in rapid loss in altitude. Aircraft are particularly vulnerable to wind shear on approach and departure, where altitude may be insufficient to allow recovery. Wind shear is reported to have caused at least two major air carrier crashes in the past decade, with resulting heavy loss of life [2].

In response to this threat, the Federal Aviation Administration (FAA) is sponsoring research on Doppler weather radar for the detection of low-level wind shear. If it can be demonstrated that these hazards can be detected by radar and warnings rapidly disseminated to air traffic control (ATC), the FAA will seek approval to install Doppler weather radars at up to 100 terminal areas [3]. Although the optimum design has not been determined, the current consensus is that these radars will operate at 5 cm. wavelength and have 1.0 to 1.5 degree pencil beam antennas with very low side lobes. Each radar will observe the terminal area in a series of fixed-elevation angle scans such that the airspace observation is updated every 1 to 2 minutes.

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At present, identifying wind shear hazards from Doppler radar displays is done largely by meteorological experts working in the research environment. However, this interpretation function must be automated to support air traffic control operations for two reasons. First, not enough experts exist to monitor for wind shear hazards at all the radar sites. Second, the task cannot be delegated to air traffic controllers because of the meteorological expertise required and the accompanying increase in workload.

The objective of the WX1 project is to develop a system which mimics the ability of a radar meteorologist to recognize wind shear hazards from single-Doppler weather radar displays. The WX1 design employs techniques from artificial intelligence and machine vision in order to emulate the symbolic reasoning and image processing capabilities of the meteorologist. WX1 uses a rule-based expert system coupled to an object-oriented image processing package to achieve these aims.

SYSTEM DESIGN

The WX1 system, currently implemented on a Symbolics 3670 Lisp machine, consists of two major elements, observer and expert, as shown in Fig. 1. The observer element contains the numerical and image processing capabilities of the system; the expert element contains the system's meteorological knowledge and symbolic reasoning capability. The two elements communicate via message passing, with the observer generating responses to queries from the expert.

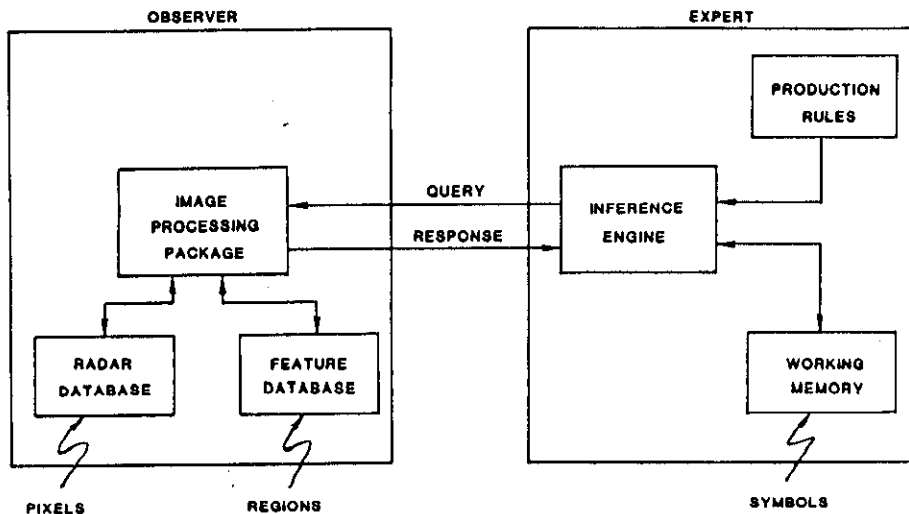


Fig. 1. WX1 System Design.

The observer element consists of an image processing package operating on radar and feature databases. The tasks allocated to the image processing package are to 1) construct the radar database from the input data, 2) extract features from the radar images, and 3) build the feature database under control of the expert element. As shown in Fig. 2, the flow of processing is initially top-down to construct the radar database, and then bottom-up to assemble the feature database.

The image processing package is implemented with extensive use of the Flavors object-oriented programming system [4]. Each node in the radar and feature databases is represented as a *flavor instance*, and image processing procedures are attached to each node as flavor methods. These procedures are then invoked via messages from the expert element.

The expert element consists of the standard expert system components: production rules, working memory and inference engine. It is implemented in YAPS, a production rule language similar to OPS5 [5]. The production rules are of two types: representation and procedural. Representation rules encode relational models of wind shear hazards; procedural rules express heuristics about how to instantiate these models.

The expert system working memory contains a symbolic representation of the contents of the radar and feature databases, as illustrated in Fig. 3. Whenever a node is created in either database, a corresponding fact is added by the expert system to its working memory. For example, suppose that V1 is a Doppler velocity field, and that F1 and F2 are features extracted from it. These nodes in the radar and feature databases are represented as facts in working memory. Each fact contains a pointer to

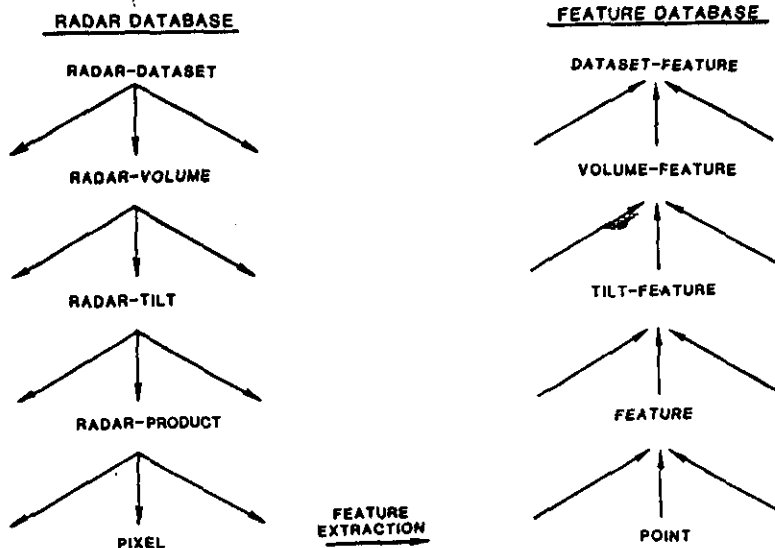


Fig. 2. System Processing Flow.

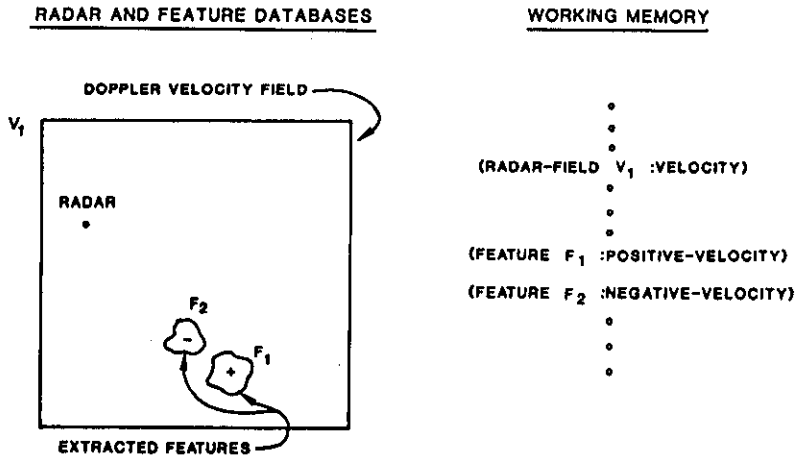


Fig. 3. Dual Representation Scheme.

its parent node, establishing a link between the symbolic and object-oriented representations. The advantage of this dual representation scheme is that it allows WX1 to reason symbolically about the data while retaining a powerful underlying image processing capability.

Observer Element

Radar Data Processing

The input radar data is structured into datasets comprising a time sequence of observations from a single Doppler radar for a given airspace volume. Each volume scan consists of set of fixed-elevation scans or "tilts", generally starting from surface elevation and going up to as high as 15 to 20 degrees. Each tilt contains the radar products gathered for that scan. The radar products of primary interest are reflectivity and Doppler velocity, which will now be briefly discussed.

The reflectivity product provides a measure of rainfall rate, and is expressed in dBZ, the logarithm of the range-adjusted reflectivity. The radial velocity product is a measure of wind velocity in the direction of the radar. Note that wind movement perpendicular to the radar beam cannot be directly measured by a single Doppler radar.

In addition to these primary products, there are two more products that can be derived from the radial velocity: radial shear and azimuthal shear. Radial shear is the derivative of the radial velocity in the direction along the radar beam, and azimuthal shear is the velocity derivative taken in the direction perpendicular to the beam. As will be shown later, radial shear is used to identify regions in the wind field of inflow (convergence) or outflow (divergence). Azimuthal shear is used to find regions of rotating winds and to aid detection of inflow/outflow lines.

The input radar fields are converted from polar to Cartesian-sampled form by off-line processing prior to entry into the radar database. Various numerical processing operations can be carried out on these radar fields by the image processing package. One type of processing is to modify an input field by such operations as filtering, masking and thresholding. Another class of operations is to compute derived products such as radial shear.

Each dataset in the radar database is a tree structure was shown in Fig. 2. The nodes of the tree are flavors objects and methods are attached to each object flavor for carrying out radar processing operations. For example, a filtering operation is carried out by sending the ":filter" message to a radar-product object. Similarly, creation of a derived product can be carried out by a message to a radar-tilt object.

Feature Extraction

Feature extraction involves three steps: pixel classification, connected-region determination and feature instantiation. Pixel classification is based on a priori assignment of pixel values to classes. For example, pixels in the radial velocity field are classified as positive (> 2.5 m/s) or negative (< 2.5 m/s). The result of this process are point maps of the classes for each field. The connected regions for each point map are then determined, resulting in a list of regions for each class. The result of the feature extraction operation on a Doppler velocity field is shown in Fig. 4, with the bounding rectangles of each feature drawn for clarity.

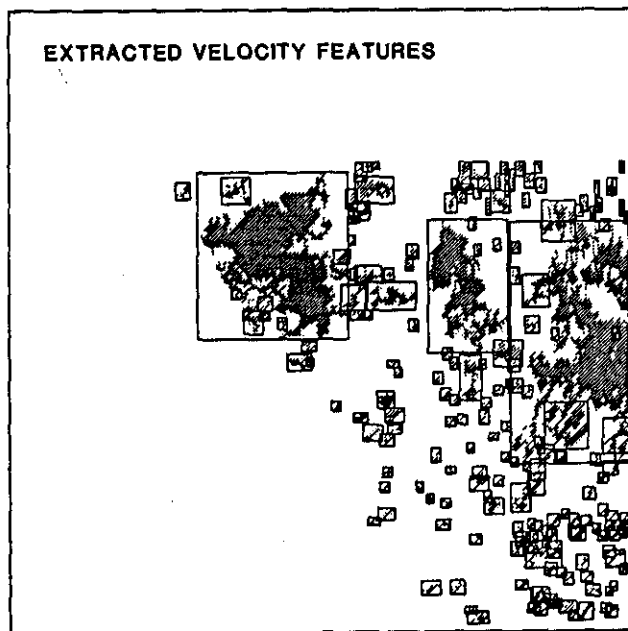
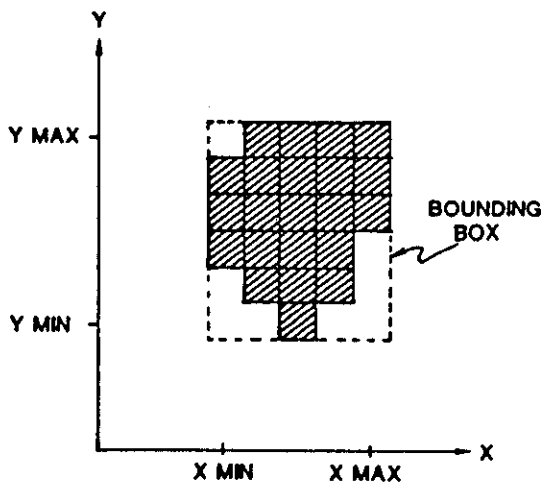


Fig. 4. Feature Extraction Example.

Once the connected regions for each class are determined, each region above a threshold size is instantiated as a feature object and entered into the feature database. At the time a feature is instantiated, some of its elementary properties are recorded as instance variables. These properties include number of pixels, bounding rectangle and parent radar field, as shown in Fig. 5.



#<FEATURE 1>, an object of flavor FEATURE,
has instance variable values:

```

RADAR-FIELD: #<RADAR-FIELD VELOCITY 1>
FEATURE-NUMBER: 1
FEATURE-SIZE: 30
FEATURE-CLASS: :POSITIVE-VELOCITY
XMIN: 162
XMAX: 166
YMIN: 130
YMAX: 135

```

Fig. 5. Example of a Feature.

Feature Processing

Three types of operations can be carried out on features. The first type of operation is to answer a query about the properties of a particular feature. These properties include: 1) location (centroid, range to radar, azimuth, altitude), 2) shape (length, width, height, elongatedness, compactness), and 3) numeric values (maximum, minimum, average). These properties are computed by methods attached to the feature flavor, and are invoked by messages to the feature, e.g. "(send F1 :centroid)" causes the centroid of feature F1 to be computed.

The next type of operation involves determining relationships between features. The response to these queries can be either numeric or logical. An example of a numeric result is to compute the distance between two features, e.g. "(send F1 :distance F2)" computes the distance between the centroids of F1 and F2. An example of a logical result is to determine whether two features overlap, e.g. "(send F1 :overlaps-p F2)" returns T if the bounding rectangles of the features overlap and nil otherwise.

The third type of operation is to create higher-level features from lower-level features. A higher-level feature is created by the image processing package when the expert element finds that there is a reason to group features together. For instance, the expert element may decide that features F1 and F2 constitute what is termed a velocity couplet signature. The expert then asks the image processing package to create a higher-level feature from F1 and F2 called a tilt-feature. This tilt-feature is added to the feature database and also as a fact in working memory. Tilt-features can be combined to produce volume-features, and volume-features can be combined to produce dataset-features. These higher-level features can also respond to queries about themselves and their relationships to other features.

Expert Element

Whereas the observer element deals with radar images in a concrete and detailed fashion, the expert element operates on them in an abstract, symbolic manner. In fact, the details of a feature's exact form are not available to the expert element at all. Rather, each feature is known only to the expert element as a blob with certain general properties, such as product type (radial velocity, radial shear, azimuthal shear) and classification (positive velocity, negative velocity, etc.). However, the detailed properties of each feature can be queried by the expert via messages, as will now be discussed.

As an example, consider problem of detecting a velocity couplet signature. The YAPS rule to perform this task might appear (in simplified form) as follows:

```
(p recognize-velocity-couplet
  (feature -pv :positive-velocity)
  (feature -nv :negative-velocity)
  test (<= (send -pv :distance -nv) 4.0)
  --> (setq -vc (make-instance 'tilt-feature (list -pv -nv)))
      (fact velocity-couplet -vc)
  )
```

For the situation that was shown in Fig. 3, the variables $-pv$ and $-nv$ in the rule would be matched with features F1 and F2, respectively. The test portion of the rule then invokes the computation of the distance from F1 to F2, and checks that the result is less than 4.0 kilometers. If all of these left-hand side conditions are fulfilled, then the right-hand side action is carried out. In this case, the action is to create a tilt-feature from F1 and F2, and then add the corresponding fact to working memory.

The simple rule shown above constitutes part of a model for a wind shear hazard called a surface microburst. As shown in Fig. 6, the model is a tree structure with features of different types as its leaves. In order to recognize this wind shear hazard, the expert element must instantiate part or all of this structure. The expert knowledge of the system lies in both the structure of the model and in the heuristics for how to go about instantiating the model.

Although the goal of the knowledge processing is to achieve bottom-up assembly of the low-level features into high-level wind shear hazards, the process of assembly requires a combination of bottom-up, top-down and parallel support. For example, recognizing a velocity couplet involves bottom-up assembly of positive and negative velocity features. A divergence signature, on the other hand, can be recognized by either a velocity couplet or a suitable positive radial shear feature. Activation

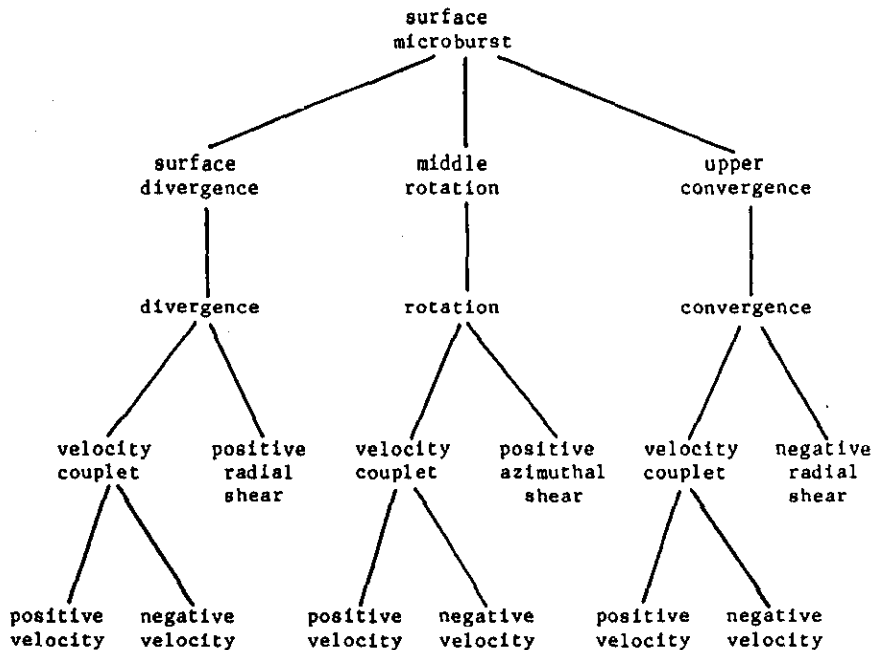


Fig. 6. Model of a Microburst Wind Shear Hazard.

of both pathways would constitute parallel support for the divergence signature. Finally, if only the positive radial shear feature supporting the divergence signature were found, then a top-down expectation would be generated to attempt to find the missing velocity couplet.

The heuristic search aspect of the knowledge processing involves how to avoid examining all of the very large number of possible model instantiations. If the velocity field contains 50 features of each class (positive and negative), then 2500 potential velocity couplets exist. Rather than examine all of these possibilities, the expert attempts to constrain the search by initially examining only those features which seem likely to be of interest. Less likely features are only considered on the basis of support from above and proximity to likely features. In this manner, the search space is constrained to a small subset of the potential possibilities. In addition to improving efficiency, false recognitions are also made less probable, since consideration is limited to high confidence features.

Several comments are appropriate on the use of rules in this image understanding process. First, rules allow both the models and the search heuristics to be rapidly and easily modified. Second, they seem to express in a natural way the heuristics radar meteorologists use to carry out the recognition task. Third, the manner in which YAPS rules are used in WX1 allows declarative models to be conveniently coupled to image processing procedures.

WIND SHEAR HAZARD RECOGNITION

Rulesets are currently being developed to recognize two types of low-altitude wind shear hazard: microbursts and gust fronts. This section will describe the characteristics of these hazards, their associated single-Doppler radar signatures, and some initial recognition results.

Microbursts

A microburst is a small-scale, short-lived event characterized by a strong downdraft which induces a hazardous outflow of winds at the surface. Fig. 7 shows an aircraft encountering a microburst while landing. The combination of downdraft and loss of airspeed while passing through a microburst is reported to have been the cause of major air carrier crashes in 1975 and 1982 [2]. Microbursts are less than 4 km in initial horizontal extent and last 5 to 10 minutes. For a typical microburst observed in the Joint Airport Weather Study (JAWS) project, the surface differential velocity typically increased from 12 m/s (25 knots) to a maximum of 24 m/s (50 knots) in this time interval [6].

Several different varieties of microbursts have been identified by Fujita [2]. For the JAWS data currently being investigated, microbursts appear to be characterized by a surface level outflow (divergence), middle-altitude rotating winds and an upper-level inflow (convergence). Fig. 8 shows the characteristic single-Doppler radar signatures associated with these flow fields. The model of Fig. 6 discussed previously shows the connection between these radar signatures and the microburst model.

Fig. 9 shows an example of a JAWS microburst which occurred 13 km. east of

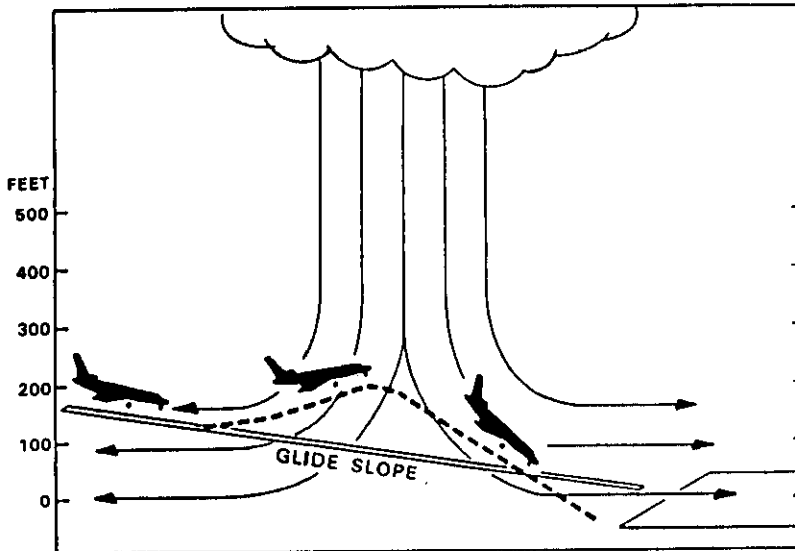


Fig. 7. Aircraft Encounter with a Microburst.

	FLOW FIELDS	VELOCITY SIGNATURES	SHEAR SIGNATURES
INFLOW			<p>RADIAL</p>
ROTATION			<p>AZIMUTHAL</p>
OUTFLOW			<p>RADIAL</p>

Fig. 8. Single-Doppler Signatures of a Microburst.

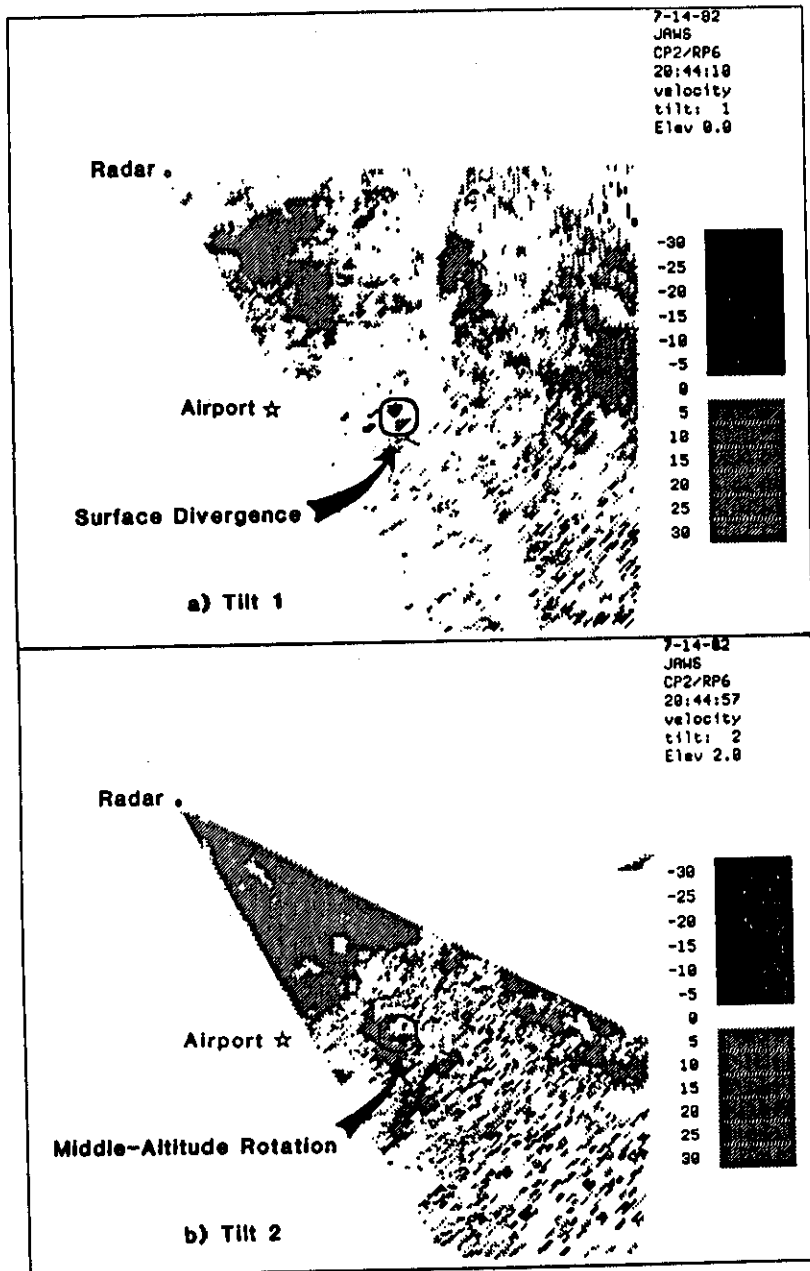


Fig. 9. Radar Data for Microburst.

Stapleton Airport on 14 July 1982. The microburst began around 2:33 p.m. and reached peak intensity ten minutes later [7], at about the time the data of Fig. 9 were collected. Radial velocity data are shown for scans at the surface (tilt 1, upper panel) and at 2.1 degrees elevation (tilt 2, lower panel). The cursors show the location of a surface divergence signature in tilt 1 and a middle-altitude rotation signature in tilt 2. The images are 256 by 256 pixels at 0.25 km per pixel.

The first step in the microburst processing is to extract features from the input radar fields. Whereas the velocity and radial shear fields are processed for tilt 1, the velocity and azimuthal shear fields are used for tilt 2. Different fields are extracted for the two tilts because the system is looking for surface divergence signatures in the first tilt and for middle-altitude rotation signatures in the second. Upper-altitude data was not available in this case, so there was no attempt to perform extraction for convergence signatures.

The microburst ruleset evaluates the extracted features, promoting likely regions to candidate status as shown in Fig. 10 and labelling the others

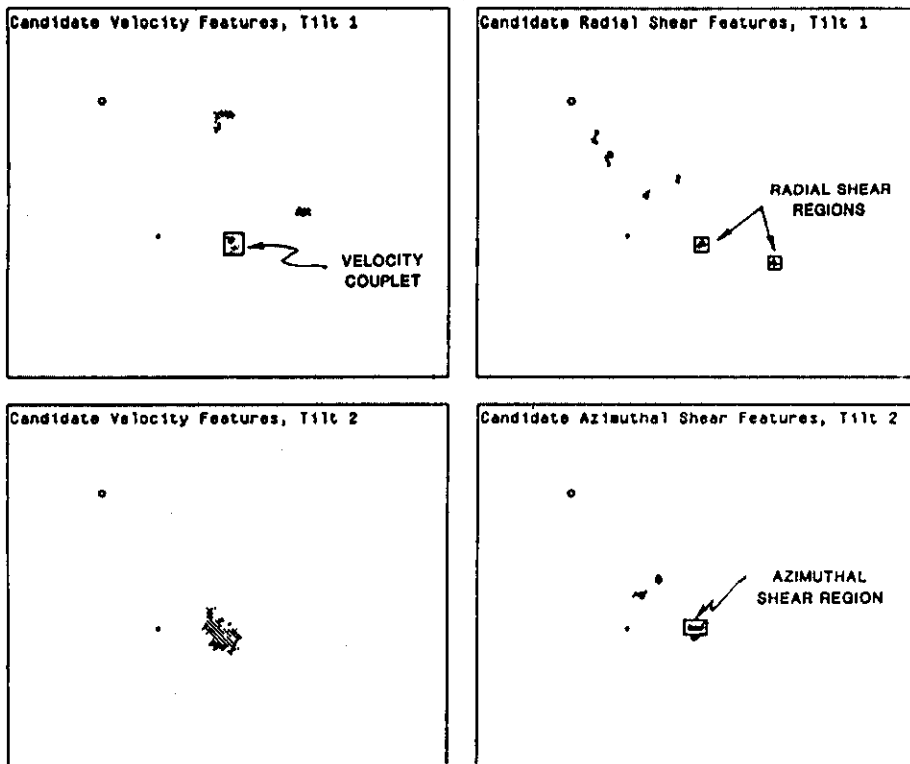


Fig. 10. Surface and Middle-Altitude Microburst Tilt-Features.

as weak. The candidate features are then evaluated as microburst indicators. Initially, the features for the velocity couplet of tilt 1 are labelled as weak due to their small size. However, these features are promoted to candidate status on the basis of their overlap with one of the radial shear signatures. The velocity couplet is then recognized as a surface divergence.

The candidate features for tilt 2 are examined in a similar fashion. A middle-altitude rotation is identified from one of the azimuthal shear features, but the velocity couplet signature is not recognized because the positive velocity feature is too large. However, the system determines that the azimuthal shear rotation signature overlaps the divergence signature in tilt 1, and therefore declares that a microburst has been detected. This result is indicated in Fig. 11, showing the overlap of the surface divergence and middle-altitude rotation features.

Fig. 12 summarizes the results of processing seven volume scans of JAWS data for 14 July 1982 lasting fourteen minutes from 1431 to 1445 MDT. Two microbursts were detected in this interval, the first during 1431-1434 and the second during 1442-1445. The centroids of the microbursts detected in each volume scan are plotted in the figure.

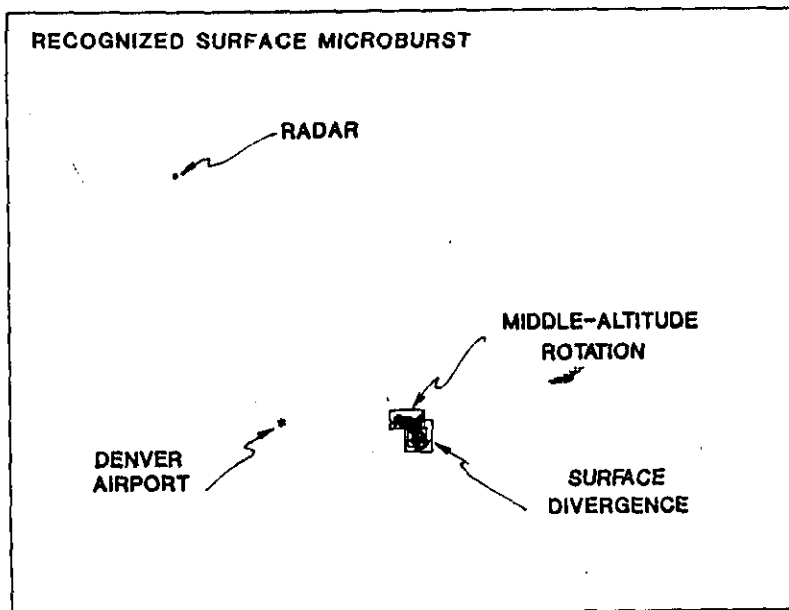


Fig. 11. Recognized Microburst Volume-feature.

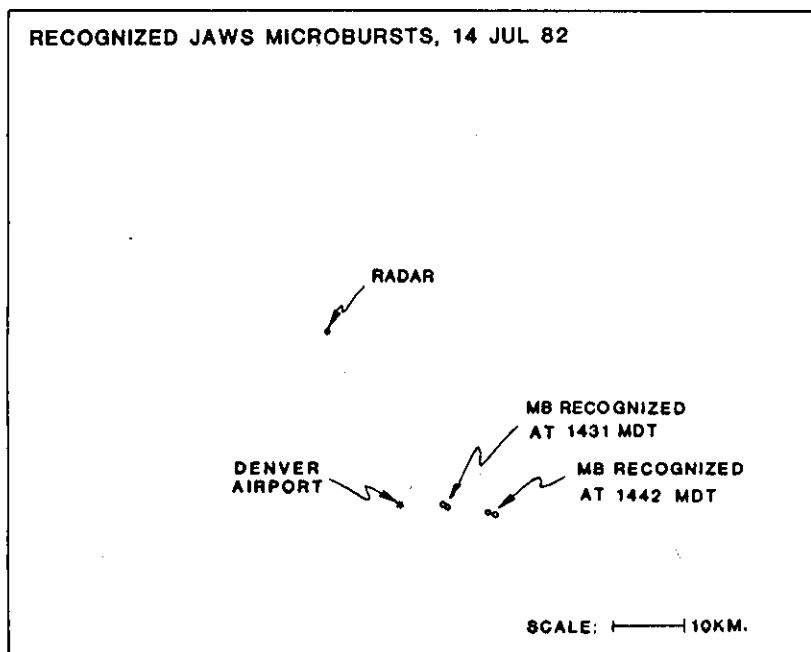


Fig. 12. Recognized JAWS Microbursts.

Gust Fronts

A gust front is the leading edge of a cool air mass that has recently descended from a thunderstorm or convective cloud [1]. This air mass spreads out at the surface and is often found many kilometers away from the parent storm, as shown in Fig. 13. Although gust fronts pose less of a threat to aircraft than microbursts, they can cause an aircraft passing through one to experience turbulence and buffeting. Also, the ability to detect gust fronts is useful in predicting wind shifts that cause active runway changes [8].

As shown in Fig. 14, a gust front is characterized by a region of cold air outflow converging with a warm air inflow. This convergence creates a long, thin line of negative radial shear, independent of whether the gust front is moving toward or away from the radar. In addition, azimuthal shear can be combined with negative radial shear to improve detection of curved or noisy shear lines.

The gust front ruleset, as described in a thesis by Olson [9], initially looks for shear regions that have a high probability of representing a gust front. These regions are declared to be high confidence features on the basis of such evidence as proper shape, proper size and high correlation with shear regions in adjacent tilts. These high confidence features are then used as islands of reliability to guide the processing of regions with weaker evidential support.

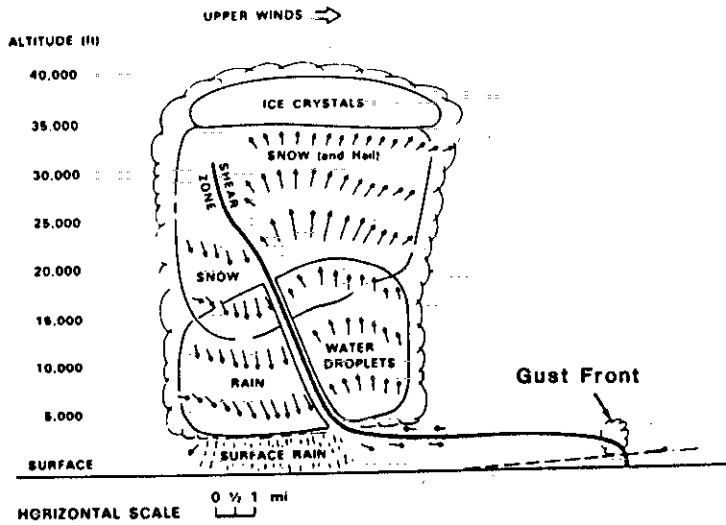


Fig. 13. Aircraft Encounter with a Gust Front.

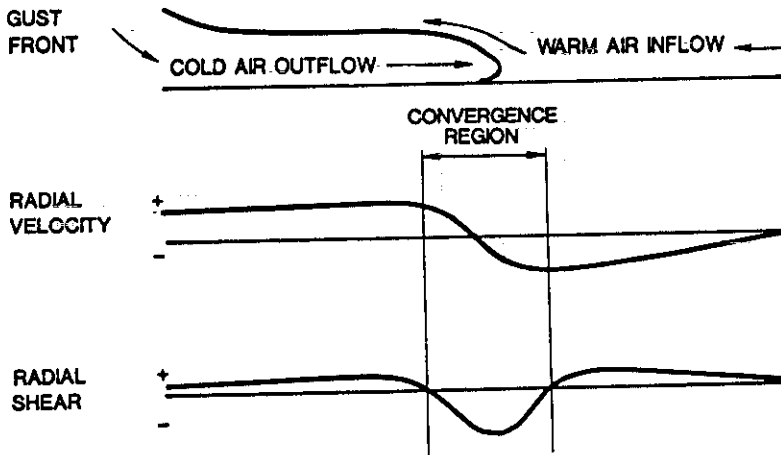


Fig. 14. Gust Front Convergence Signature.

An example of this process is illustrated schematically in Fig. 15. In tilt 1, the line of shear is long and unbroken, and thus it is labelled as a high confidence shear region. In tilt 2, however, the line of shear is split into two regions due to noise, missing data, or imperfect feature extraction. The resulting segments are therefore assigned as candidate or lower confidence regions. But because these two segments overlap a high confidence region on an adjacent tilt, the expert system directs the image processing package to grow (enlarge) the two regions and examine them again. This process is termed re-extraction. In this case, the two regions now touch and are merged into a single region which can now be assigned high confidence.

When one or more features in a tilt are recognized as representing a gust front shear line, WX1 assembles them together into a tilt-feature. If the

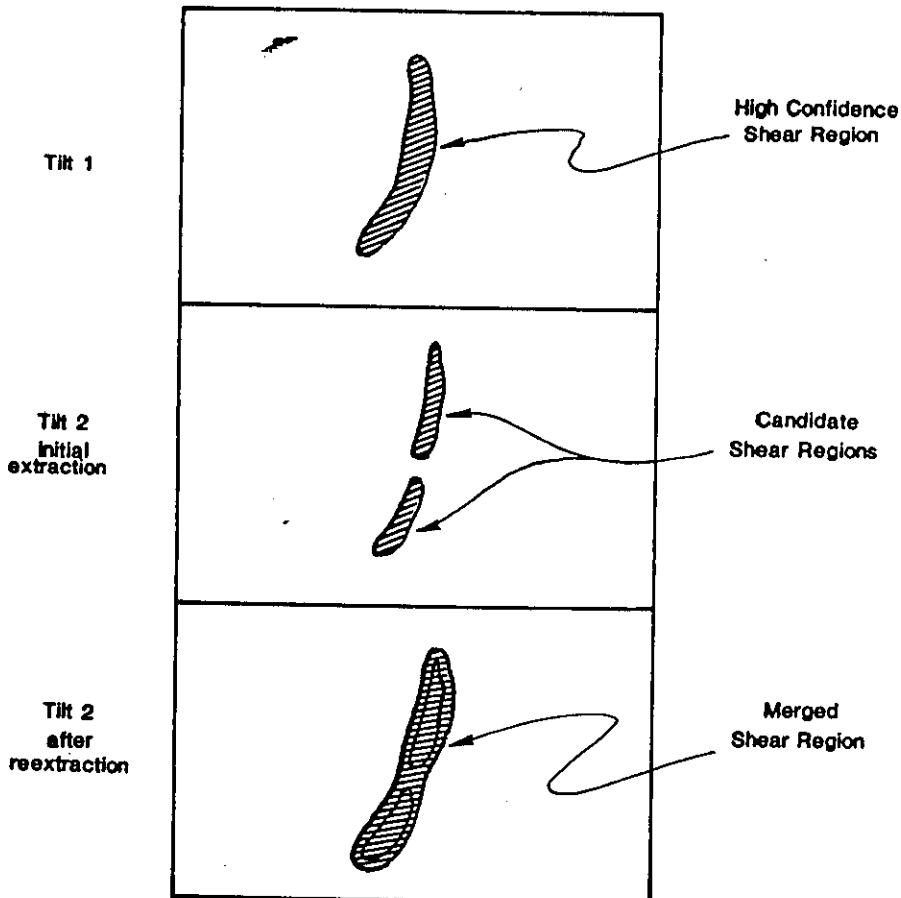


Fig. 15. Use of Evidential Support to Guide Gust Front Processing.

shear lines in adjacent tilts overlap sufficiently, they are assembled to form a volume-feature. Volume-features, in turn, can be assembled into a dataset-feature representing the recognition of a gust front over a sequence of radar observations.

To illustrate this process, consider the radar data of Fig. 16. This data was gathered by the National Severe Storms Laboratory (NSSL) at Norman, OK, and shows a large convective storm moving eastward [10]. The dataset includes four volume scans covering a fifteen minute period. The figure shows the surface elevation scan for the first volume. A squall line is seen in reflectivity field (upper panel) and a line of convergence is seen in velocity field (lower panel). The scale is 1 km per pixel for these 256 by 256 pixel images.

Fig. 17 shows the volume-features detected by the gust front ruleset for each of the four volumes (labelled volumes 1 through 4 in the figure). Note in particular that the volume-feature for volume 2 is broken into two distinct parts. Nonetheless, the ruleset recognizes these two segments as representing a single gust front shear line. These volume-features are linked together to form a dataset-feature as shown in Fig. 18. For clarity, each volume-feature is shown as a rectangle indicating its centroid, and a line indicating its orientation and approximate length.

SUMMARY

The design of a prototype weather radar interpretation system has been presented. The WX1 system couples a rule-based expert system to an object-oriented image processing package via a dual representation scheme. Features extracted from radar images are represented both as symbols in the expert system's working memory, and as objects in the feature database. This dual representation allows the expert system to reason symbolically about radar images and to invoke image processing operations via messages to feature objects.

Rulesets are currently under development for recognizing microburst and gust front wind shear hazards. The initial results presented demonstrate the ability of the WX1 system to detect hazards of these two types. Capabilities illustrated by these results include: 1) matching of radar image features to declarative models expressed in the form of rules, 2) use of heuristic search methods to limit the solution space and avoid false detections, and 3) adaptive processing of extracted features to compensate for errors in radar data and segmentation procedures.

Future efforts will include testing with a wider variety of datasets, refinement of the existing ruleset to increase system robustness and expansion of the rules to include additional models, such as other types of microbursts.

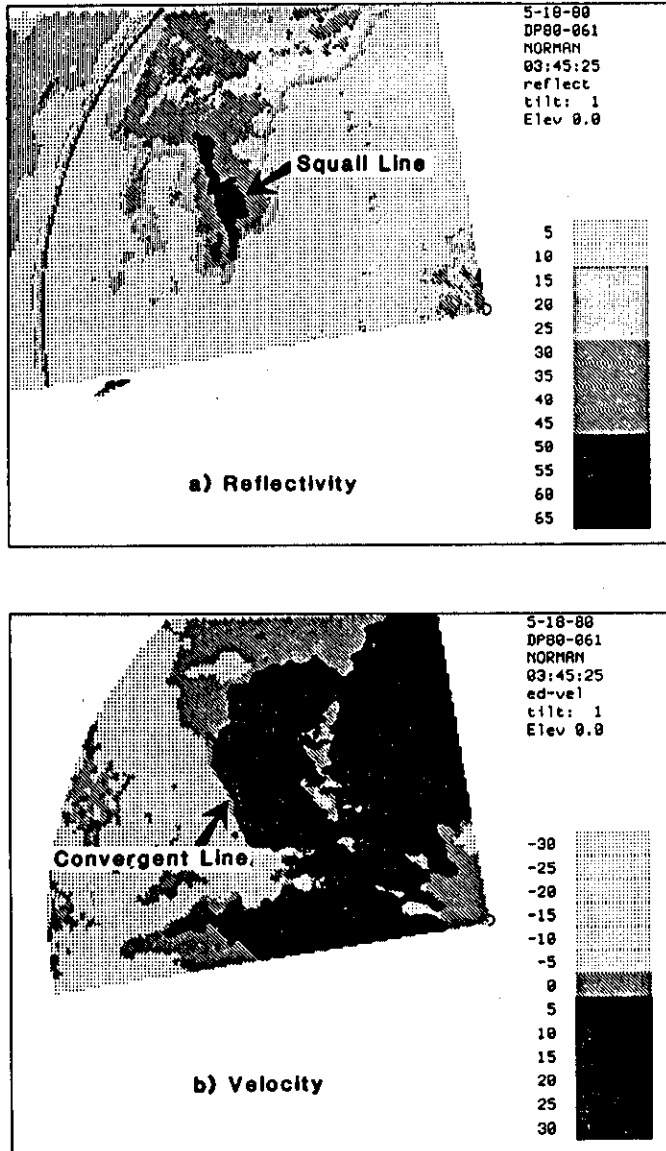


Fig. 16. Radar Data for Gust Front.

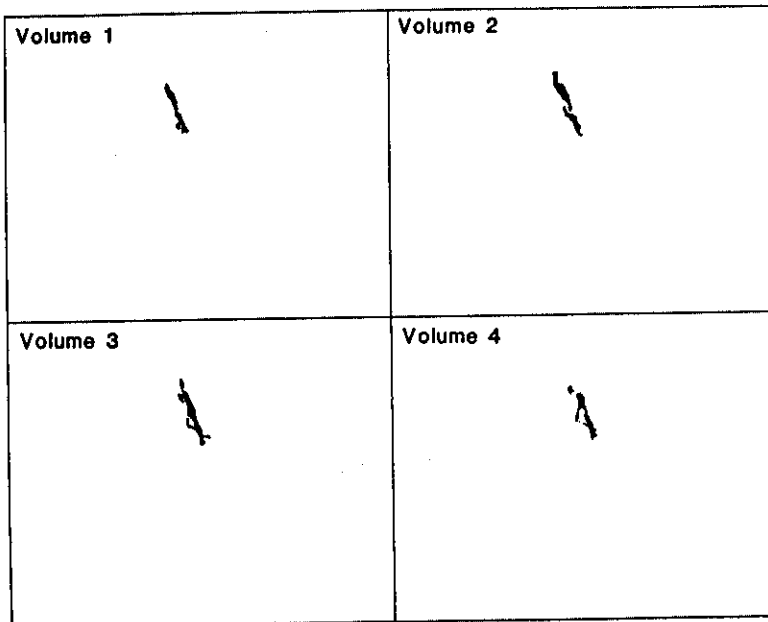


Fig. 17. Recognized Volume-features for Gust Front.

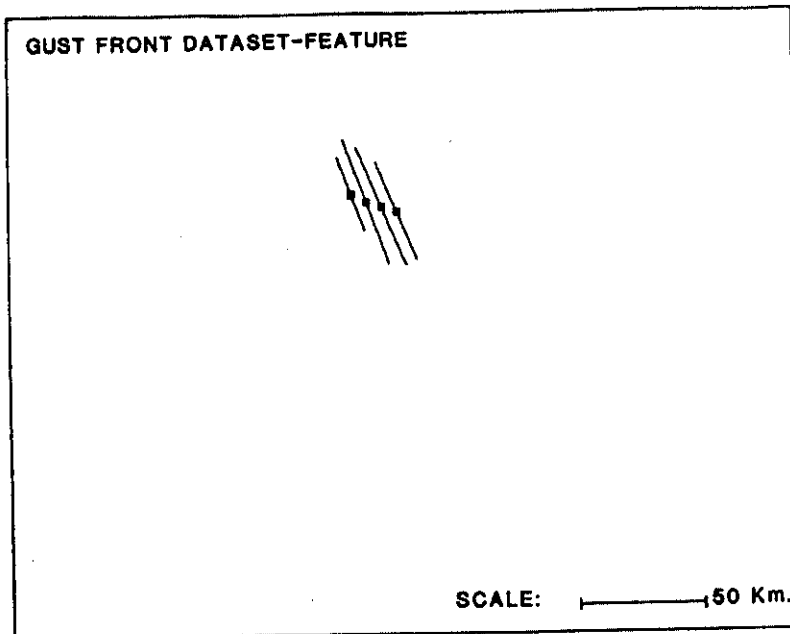


Fig. 18. Dataset-feature for Gust Front.

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