Convective clouds modelling and tracking by an airborne radar

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***Abstract*— A method for modelling and tracking convective clouds within radar images is described. Clouds are non-rigid heterogeneous objects; a good representation of the weather scene is performed by extracting skeletal lines of the 2-dimensional grayscale pictures. Skeletons are reduced to sets of segments within a graph structure and tracked among successive pictures by means of relaxation labelling processes. We present preliminary results of our method on airborne weather radar data.**

The conventional morphological skeleton constraint —i.e., to be centered in relation to the object boundaries— is here replaced by attachment to the gray levels local maxima. The resulting skeletal line is forced to go through each intense convective cell, and links neighboring ones into a global structure. Moreover, each feature point can be labelled and enriched by meteorological information. Such pattern is particularly suitable for weather nowcasting, since the user (for example, an aircraft's crew) is specially interested in the convective cells evolution.

I. INTRODUCTION

Weather surveillance is a crucial issue for aeronautical industry. Ground-based radars of air traffic surveillance stations and airborne radars on civil aircrafts provide real-time information and prevent from main weather threats. Aircrafts must particularly avoid high convective cells (Cumulonimbus), since they are likely to indicate hail precipitations, lightnings, icing and turbulence phenomena. For example, severe tropical storms clouds can reach 15 km height, and so exceed common commercial routes altitude. Such storm is typically composed of numerous clouds, which are likely to advect, merge, split and/or collapse. The pilot must choose a route, taking into account relative position, intensity of convection, trajectory and life cycle of each cloud (cf. Fig. 1). In order to improve the decision-making process, a method for tracking and nowcasting clouds motions is required.

II. PROBLEM ANALYSIS

A. General approach

We are interested in providing accurate information on the weather situation / evolution to aircrafts pilots. The main information sources are ground-based weather station and airborne weather radar. In case of transoceanic flight, the airborne radar can be the unique available sensor. Transmission of synthetic information between successive aircrafts following the same route is also possible.

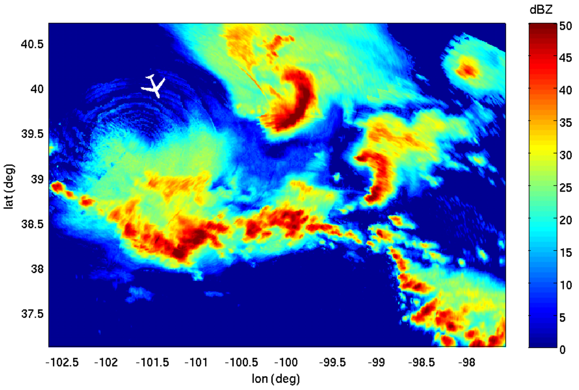

Fig. 1. Example of an aircraft facing a severe weather situation (thunderstorm, Kansas, 07/22/2000)

In case of radar with vertical agility, a huge quantity of data is available: 3-dimensional scans repeated every few minutes. Traditional radar display is composed of a 2D range-azimuth snapshot demonstrating the weather environment (position of convective cells). The vertical exploration is also useful, since it provides the storm top altitude of each cloud. The life cycle of the cloud can be deduced from this storm top evolution: growing, stable or collapsing phases are directly connected with the storm top altitude tendency.

These considerations lead to analyse description models which synthesize useful information, in order to transmit a small amount of data on ground-air and air-air links. Moreover, the forecasting task must be based on robust parameters, describing the cumulonimbus evolution in term of horizontal motions, vertical tendency, and dynamic behavior: merging, splitting, convection intensity, etc.

B. State of the art

The issue of tracking weather targets is currently addressed in literature, generally applied to satellite data. The context of this study leads to consider particularly the proposed description models.

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A simple thresholding operation is often computed to extract the targets, as in [1]–[3]; in [4], authors make use of two combined thresholds, on intensity of pixels and on objects area. A finest detection criterion is used in [5], since the clouds boundaries are extracted according to the level set method introduced by Sethian [6].

Clouds characterization may be based on geometrical parameters (area, gravity center, deformation, etc.) as in [1], [2], [4]. More abstract parameters can also be computed: in [1], authors propose to sample clouds boundaries and to construct a matrix H of distances between each pair of points on the boundaries. Each cloud is then characterized by the eigenvectors of the associated matrix H. In [4], a texture descriptor and contour Fourier descriptors are computed. Other interesting methods are based on visual descriptive parameters: active contours in [5], morphological skeletons in [3].

Finally, the tracking step is performed by evaluating overlapping area in [2], [4], distance between characteristic points (e.g. gravity center) or between descriptors in [1], [4]. Relaxation labelling processes are implemented by Barbaresco in [3].

This short overview shows that global synthetic description of clouds is rarely found in literature. In most cases, numerous descriptors are used, few of them giving a general survey of the cloud shape and intensity.

C. Available data

Algorithms described in this paper have been applied on simulated X-band airborne weather radar data. Weather situations are extracted from Nexrad radar network (S-band ground-based weather radar). Microphysic (hydrometeor types) is deduced and X-band signal is simulated, given the aircraft position and route, and the radar characteristics (beam aperture, signal-to-noise ratio, etc). Inputs for forecasting are two radar scan with interval of 5 minutes. The aircraft is supposed to fly at 540km/h (290 NM/h).

Reflectivity is expressed in dBZ, which is the traditionnal unit for weather radar data.

At present, the simulation includes neither path attenuation due to weather clutter, nor ground clutter.

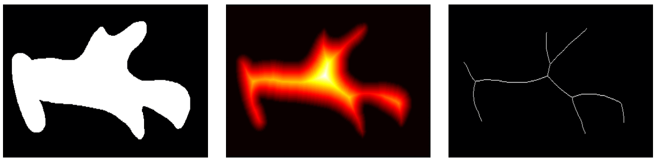
III. THE METHOD

We resume F. Barbaresco's work on morphological skeleton [3], as the method gives good prediction results. Moreover, morphological skeleton is an interesting shape descriptor, especially for deformation tracking. We will modify the extraction method, in order to reinforce the skeleton's dependency upon convection hearts.

A. Skeleton and grayscale skeleton

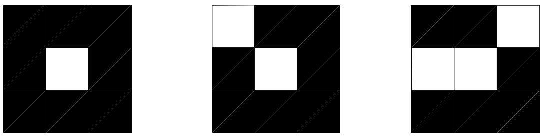
Morphological skeleton is computed starting from a binary picture (e.g. resulting of a thresholding operation on a graytone picture). The skeleton SK of an object X is defined as the locus of centers of maximal disks contained within the object's boundaries :

$$\begin{aligned}& s \in SK(X) \\ \Leftrightarrow & (\exists\, y_1, y_2 \in \partial X, y_1 \neq y_2 \mid d(s, \partial X) = d(s, y_1) = d(s, y_2))\end{aligned}$$



(a) Shape (b) Distance map (c) Skeleton

Fig. 2. Skeletonization process by means of a distance map



(a) peak point (b) end point (c) ridge point

Fig. 3. Specific points that must be protected during the thinning process

with ∂X denoting boundaries of the object X.

A usual method to extract the skeleton is to compute a distance map, which is the distance between each point of the object and the nearest point of the boundaries. Then the digital euclidian skeleton algorithm of Fernandez-Vidal et al. [7] can be applied, as suggested in [3]. Fig. 2 illustrates this method on an example.

Therefore morphological skeleton is centered in relation to the object boundaries. However, there is no relationship with the most intense parts of the object. As said before, we are looking for a way to represent cloud systems with respect to their global shape, and the relative positions of the convective cells within them. We then use the notion of grayscale skeleton as defined by Arcelly and Ramella in [8]. This kind of skeletonization is performed by iterative thinning algorithm. For a grayscale image, the thinning operation consists in lowering the gray-level of each pixel identified as a simple point, i.e., whose gray level lowering does not modify topology features.

Each pixel p at the position (i, j) on the picture M is locally evaluated, with respect to its 3x3 neighborhood $V(p)$:

$$\begin{aligned} V(p) &= \{M(i+k, j+l) \mid k \in [-1 \dots 1], l \in [-1 \dots 1]\} \\ V(p) &= \begin{pmatrix} n2 & n3 & n4 \\ n1 & p & n5 \\ n8 & n7 & n6 \end{pmatrix}\end{aligned}$$

Each point of $V(p)$ is compared to the value of the central pixel p, in order to come down to a binary problem :

$$\widetilde{V}(p) = \begin{pmatrix} n2 \geq p & n3 \geq p & n4 \geq p \\ n1 \geq p & 1 & n5 \geq p \\ n8 \geq p & n7 \geq p & n6 \geq p \end{pmatrix}$$

In this frame, the pixel p can be classified easily. In [8], [9], local criteria are defined to identify each featuring point: peak, ridge or end point (examples on Fig. 3). In any other case, the point is called "simple point", and must be removed (i.e., lowered).

Finally the skeletonization algorithm is performed by studying each pixel with a chosen priority order, inverse of the pixels gray level [10]. The type of the current pixel is determined; if the pixel is labelled as being part of an object, and being a simple point, its gray-level is lowered (set to a low value corresponding to background). These steps are repeated until the image is not modified any more.

B. Skeleton postprocessing: simplification and augmentation

The result of the previous processing is a 2-dimensional picture where only the skeletal points have gray level higher than the background value. Postprocessings include linearization, meteorological data appending and skeleton pruning.

First, the amount of data must be reduced as much as possible. Featuring points of each skeleton are labelled according to their type (end points, junction, high curvature, local maxima); other points are deleted, and approximated by segments. Remaining points and segments are stored in a graph structure, in order to clearly define the neighboring relations between points.

Second, points identified as local maxima are focused, since they correspond to convective clouds, and must be characterized from the meteorological point of view. Metadata attached to such points are :

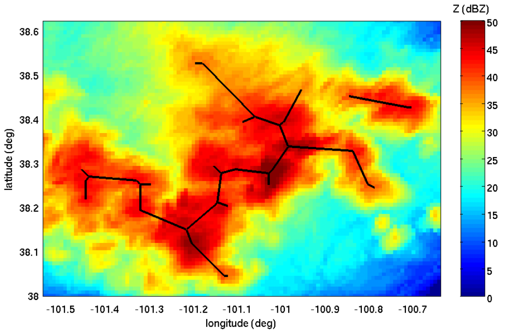
- reflectivity value (i.e., gray level)
- storm top altitude, computed thanks vertical exploration of radar data
- horizontal and vertical gradients
- if available, radar and non radar data can be added, such as temperature profile, vertical integrated liquid content, rainfall rate, etc.

Finally, skeletons are pruned in order to remove non significant branches, such as short branches generated by a large fuzzy convective area, with many local maxima (Fig. 4). Each branch is associated with a score value, which is the weighted sum of 2 criteria: branch length and mean gray-level value along the branch, each criterion being normalized by its corresponding value on the skeleton body. Branches to be deleted are selected through a simple threshold on the final score values.

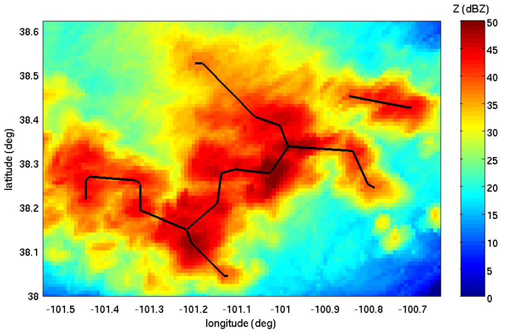
C. Tracking and forecasting

Tracking and forecasting algorithms described by Barbaresco in [3] are implemented on grayscale skeletons without modification. Graphs are compared through successive pictures; intra- and inter-images resemblance functions are computed and used as input of relaxation labelling processes. The result is a set of matching vectors, next extrapolated to produce a motion field on the whole picture.

Finally, the forecasting step can be a global shifting of pixels according to the motion vector field; or, if compression data is required, only skeletal lines are shift.

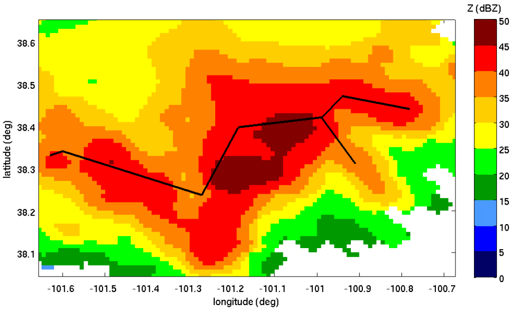


(a) skeleton

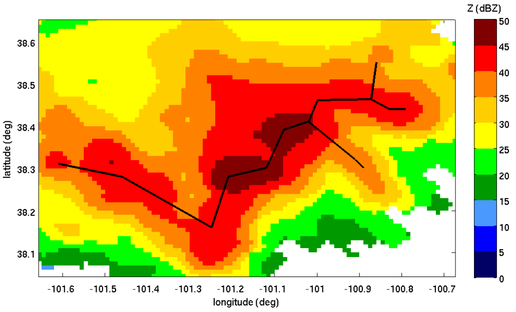


(b) pruned skeleton

Fig. 4. Effect of pruning: non-significant branches are removed



(a) morphological skeleton



(b) grayscale skeleton

Fig. 5. Morphological skeleton and grayscale skeleton (after linearization processing): by construction, relevant points lie on the grayscale skeleton

IV. PRELIMINARY RESULTS

As expected, grayscale skeleton is really suitable for modelling aspects. The example on Fig. 5 shows the advantage of this kind of skeleton. Relevant points of each cloud (from a meteorological point of view) are selected as feature points of the skeleton, while classic morphological skeleton may miss them, since it depends only on the object boundaries.

The pruning algorithm is of first importance, since the matching complexity depends on the number of extracted segments. But it can be sometimes destructive, e.g. if an intense cell is lying very close by the skeleton body: the resulting branch is especially short, thus cancelled. Improvements have to be found, in order to keep small branches which are due to relevant convective cells.

The tracking results are similar to those observed by Barbaresco in [3]; however, in case of a global cloudy system including convective cells moving non-uniformly, grayscale skeleton modelling makes it possible to detect these individual motions. Fig. 6 shows the vectors field and prediction error generated on the base of ”classic” morphological skeletons (left) and grayscale skeletons (right). Global prediction performances are lightly improved by the use of grayscale skeletons.

V. CONCLUSION AND FUTURE WORK

Grayscale skeleton definitively provides an adequate description frame for fluid and heterogeneous shape. This pattern is easily appended by meta-data; therefore, its use for compression data must be considered. Finally, linearized skeletons are robusts parameters for tracking algorithm based on shape matching.

These remarks lead to consider implementing tracking on meta-data, which could demonstrate a real advantage of the grayscale skeleton model for weather forecasting. First of all, the storm top altitude will be focused, since it is a robust criterion to determine the cloud life cycle. Other criteria could also give interesting information; e.g. horizontal gradient evolution should reveals merging or splitting events.

Other point to be investigated is weather attenuation, which is of great importance for X-band radar. Lineic attenuation may reach 2 dB/km, which strongly degrades the visible shape and intensity of clouds. A priori, boundaries should be significantly disturbed, while cores of convective cells should be quite steady. We can then reasonnably expect good performance of the grayscale skeleton-based tracking.

Lastly, although weather data are 3-dimensional, the modelling step have been processed on 2D horizontal sections, in order to minimize time costs. It is indeed well-known that convective clouds have generally the same vertical shape (column-like). Anyway, some remarkable features may sometimes appear, e.g. anvil shape. It could be so interesting to extend this work in 3 dimensions.

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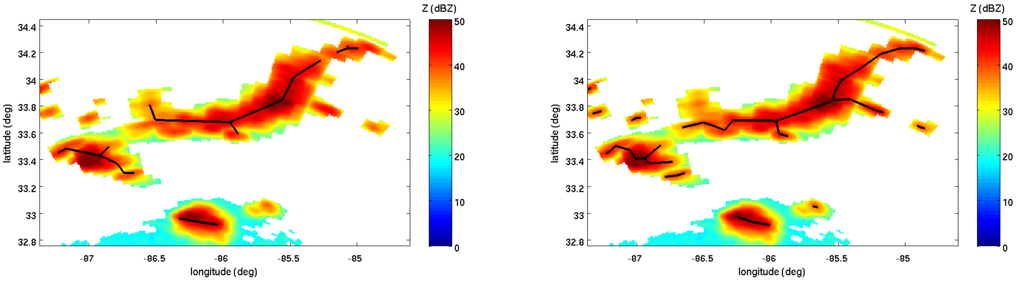
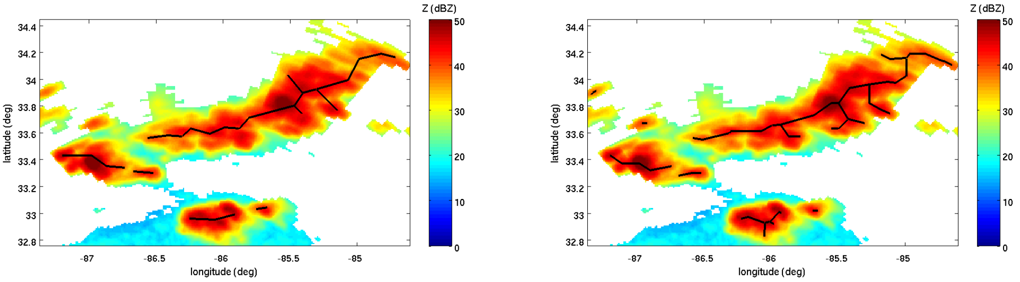
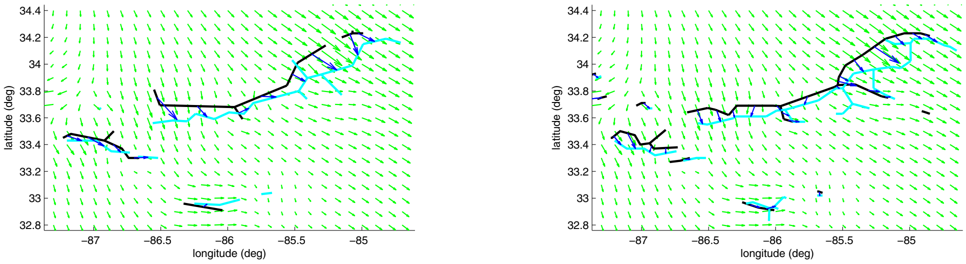


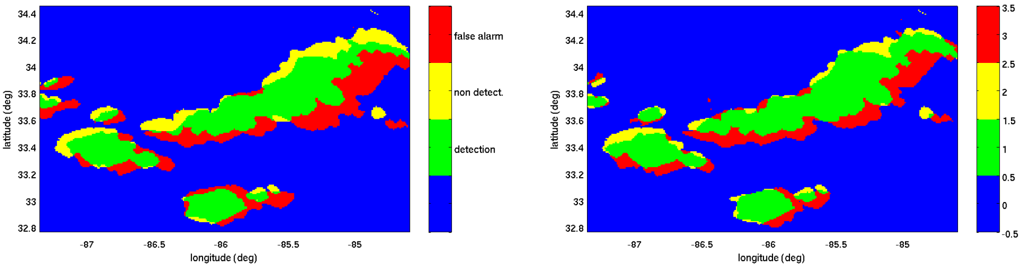
(a) t0 - morphological skeleton (b) t0 - grayscale skeleton



(c) t1 - morphological skeleton (d) t1 - grayscale skeleton



(e) motion field (f) motion field



(g) error measurement, threshold = 30 dBZ (h) error measurement, threshold = 30 dBZ

Fig. 6. Tracking results based on morphological skeletons (left): detection probability 0.74, false alarm 0.4. Tracking results based on grayscale skeleton (right): detection probability 0.84, false alarm 0.32