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1. Introduction

Conflicts between birds and commercial aircraft are a noteworthy problem at both large and small airports [Cleary, 1999]. The risk factor for United States airports continues to increase due to the steady rise in take-off/landings and bird populations. There is a significant bird strike problem in the terminal area as shown by the incidents reported in the National Bird Strike Database [Cleary and Dolbeer, 1999]. The focus of bird strike mitigation in the past has centered primarily on wildlife management techniques. Recently, an Avian Hazard Advisory System (AHAS) has been developed to reduce the risks of bird strikes to military operations [Kelly, 1999]. This system uses a mosaic of data obtained from the Next Generation Weather Radar (NEXRAD). This sensor serves as an excellent tool for enroute bird advisories due to the radar coverage provided across the majority of the United States. However, its utility in the airport terminal environment is limited due to the slow update rate and the fact that the distance of most NEXRADs from the airport results in beam heights that are too high to detect low-altitude birds over the airport.

The Federal Aviation Administration (FAA) operates two radar systems – the Terminal Doppler Weather Radar (TDWR), and the Airport Surveillance Radar (ASR-9) -- that could be used to help monitor bird activity at an airport in order to:

1. Provide continuously updated information on locations and approximate numbers of birds in flocks roosting or feeding on or near an airfield;

2. Generate real-time warnings of bird activity for dissemination to pilots of landing or departing aircraft by air traffic controllers or by direct data link.

The TDWR provides wind shear warnings in the terminal area to enhance safety, while the ASR-9's primary function is air traffic control. Both of these systems have been shown to detect biological echoes as well. Characteristics of the two radar systems have been examined and compared to determine capabilities for bird detection. Amongst other favorable factors, the high update rate and on-airport locale makes the ASR-9 a highly desirable platform for a bird detection and warning system for the terminal area.

Data from an ASR-9 at Austin TX (AUS) equipped with a Weather Systems Processor (WSP) have been analyzed to assess the ASR-9's capability to detect and monitor bird activity. The WSP add-on provides a variety of radar base data products similar to those that would be available on all ASR-9s as part of an ASR-9 Service Life Extension Program (SLEP) currently underway. The Austin airport area is subject to large flocks of wintering migratory birds as well as a resident population of bats in close proximity to the airport. Radar data, visual observations and bird strike information during periods of active bird/bat movements have been collected for this study. An automated processing algorithm called the Terminal

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Avian Hazard Advisory System (TAHAS) is being developed to detect and track roosting and migratory birds using ASR-9 data. A key challenge will be the ability to discriminate biological from non-biological targets based on variables such as vertical continuity, variance or spectral width, and horizontal velocity distribution.

2. TDWR and ASR-9 Radar Characteristics

Since the TDWR and the ASR-9 both provide airport coverage, it is informative to compare the characteristics of these radars. Several key radar system characteristics are important in determining how effective the sensor is at detecting bird targets (Table 1). The first issue to consider is the radar beam pattern, which is a 0.5-degree pencil-beam for the TDWR and a 1.4 degree azimuth by 4.8 degree elevation cosecant squared fan-beam for the ASR-9. Clearly, individual bird targets should be better resolved by the TDWR owing to the smaller beam width. Another factor that would play a crucial role in bird detectability is the location of the radar relative to the airport terminal. Since the TDWR is located off-airport, it would be more susceptible to blockage from intervening clutter sources, such as tall trees. Thus, small flocks or individual birds may be difficult to resolve from an off-airport locale even with the favorable TDWR resolution. The surface scan update rate is also of supreme importance to the reliable detection of bird echoes near the airport. The ASR-9 completes its volume scan once every 5 seconds, which is a key advantage for a timely bird detection and warning system. In clear-air mode, the TDWR surface data is updated only once every 5 minutes, which would make timely detection a difficult task. Clearly, the TDWR surface update rate needs to be increased to at least one minute to address this issue. Isaminger (1998, personal communication) has proposed a TDWR scan strategy that would achieve this objective in both clear-air and precipitation mode.

TABLE 1
Comparison of Key Radar Characteristics for Bird Detection

RADAR CHARACTERISTIC	TDWR	ASR-9
Beamwidth	0.5 deg	4.8 x 1.4 deg
Wavelength	5.3 cm	10.7 cm
Range Gate Resolution	150 meters	111 meters
Pulse Width	1.1 microsec.	1.0 microsec.
Polarization	Horizontal	Vertical/Circular
Minimum Detectable Reflectivity (50 km)	-16 dBZ	+8 dBZ
Locale	Off-airport	On-airport
Data Quality Editing	Yes	Yes
Surface Update Rate	1.0/5.0 min	5 sec

Both of these sensors have a minimum detectable reflectivity value low enough to detect most bird returns, especially at short ranges near the airport. The ASR-9 radar power-aperture product is sufficient for the detection of low cross section bird targets on the order of 10^{-4} square meters at 4 n mi. Thus, with suitable processing techniques this sensor should provide adequate individual bird target coverage over the airport environs. Another factor that could play a key role is the radar polarization. In the presence of precipitation, the ASR-9 can switch from linear to circular polarization in order to identify airplane targets obscured by weather returns. It is unclear at this time how much of an impact this could have in terms of bird detectability. Both of the radar systems employ data quality editing techniques, which could obscure or attenuate bird targets. Currently, the main considerations with the ASR-9 are the Sensitivity Time Control (STC) and the aggressive clutter filtering. However, these issues will be less of a concern if an optimized bird processing channel is developed as part of the improvements made for the ASR-9 SLEP. The primary TDWR data quality editing procedures of concern are point target editing and clutter filtering/polygon editing (Isaminger, 1996). Both radar platforms have similar range gate resolution, which should be sufficient for detecting multiple bird targets. The radar wavelength is important in terms of the radar cross-section of the feature of interest. Both of these systems utilize wavelengths that are similar to bird sizes, so there should be no distinct advantage in this regard.

3. ASR-9 Bird Detection Capability

The ASR-9 has a number of distinct characteristics that would make it suitable for detecting small targets such as birds in the airport vicinity besides the rapid update rate and on-airport locale. For one, the aircraft beacon information can be used along with the radar data to discriminate birds from airplane targets. Another facet of this radar platform is the ability to discriminate between birds and weather data due to the differences in signal amplitude between the high and low elevation beams. The WSP add-on to the ASR-9 currently being deployed by FAA at 35 existing ASR-9 sites provides enhanced weather monitoring and advisory capabilities. It generates a rich set of radar base data products, and is implemented in an easily modified architecture that allows for development and incorporation of new processing algorithms.

Data from the limited production ASR-9 WSP currently operational at AUS have been collected by Lincoln Laboratory. The WSP recording capability allows for collection of raw I,Q radar data as well as the processed base (moments) data. The I,Q data will allow for development of signal processing enhancements to produce base data products better suited for bird detection, while the recorded base data are convenient for immediate input to automated processing algorithms. An on-site meteorologist, in collaboration with airport wildlife management personnel, logs periods of observed bird activity for subsequent identification of periods for study.

AUS happens to be an excellent location for evaluating approaches to detection of biological targets owing to the presence of both bird and bat roosts in the airport vicinity. Departing birds and bats often produce radar signatures that mimic microburst and gust front signatures in the radar data. As a result, birds and bats at AUS have been identified as a recurring source of false wind shear alarms. Figure 1 summarizes the occurrence of bird and bat events detected by the WSP in the vicinity of the airport runways between the months of July through December. As shown by the chart, the detection of bats is consistent from month-to-month, with the exception of December. The data indicate that significant bat events can be expected over the airport on at least 25-50 percent of the days each month. On the other hand, the avian target hazard at this site is much more seasonal and is related to the migration of large flocks of waterfowl through the area. A number of lakes and wetlands in the airport area serve as roosting and feeding sites for birds.

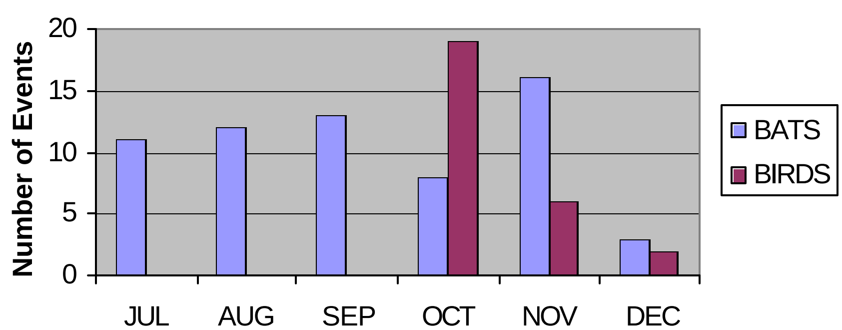

Figure 1. Bird and bat events detected by ASR-9 WSP at AUS

4. TAHAS System Architecture

Figure 2 shows the proposed architecture for the Terminal Avian Hazard Advisory System (TAHAS). The ASR-9, with its rapid scan rate and on-airport siting, will serve as the primary detection sensor. Where available, the TDWR (or a nearby NEXRAD) would provide improved altitude information and small target detection capability. The radar data will be input to a real-time processing algorithm that will identify and track bird targets within the terminal area, providing guidance for airport bird control operations and real-time warnings for air traffic control.

One or more interfaces to internal or external databases are envisioned as components of the system. The databases could assist the automated detection algorithm by providing cueing based on historically favored bird locations (e.g., roosts) as well as migratory bird information obtained from AHAS. Locations and estimates of bird flock movements generated by the system could be stored in the database for subsequent reference by airport wildlife management personnel.

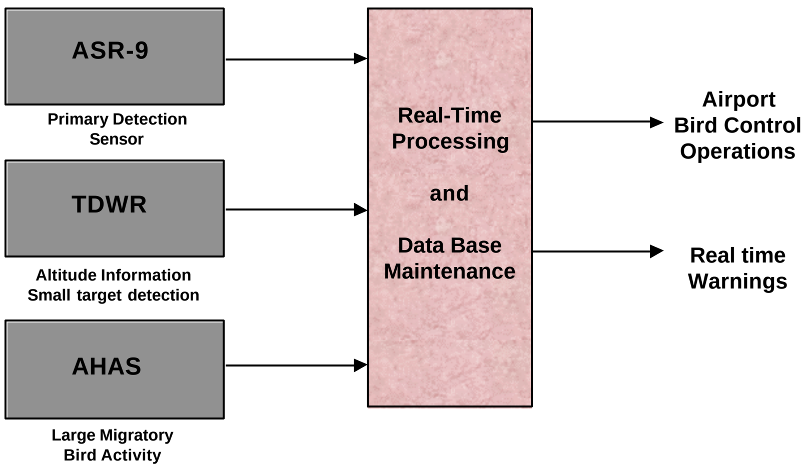

Figure 2. Proposed Terminal Avian Hazard Advisory System architecture.

5. Bird Signatures in ASR-9 WSP Data

A 1989 study by Larkin and Quine identified 11 significant diagnostic variables for distinguishing bird echoes from weather based on NEXRAD data. Isaminger (1992) examined TDWR data and expanded on the bird characteristics reported by Larkin and Quine. The most significant findings of these two studies are:

- The echo region from birds is generally less widespread than weather owing to the fact that the returns from individual point targets such as birds would conform to a $1/r^4$ model instead of $1/r^2$ due to size and coverage considerations. However, this does not always hold true since birds can also mimic a volume scatterer when they are clustered in large concentrations near a roosting site.
- The degree of stipple (a measure of variability based on differentiating the expected slope from the actual slope between minimum and maximum values along a patch of echo) is greater in biological targets (Larkin and Quine, 1989). This diagnostic variable is probably more evident in migratory versus roosting birds (Isaminger, 1992).

- Bird echoes should have a lower velocity variance or spectrum width than weather. This is due to the fact that the velocity returns from weather would typically exhibit more variability, while the velocity distribution from a bird echo is composed of similar values based on the flight speed. This seems to especially hold true for migratory birds where spectrum widths are generally one m/s or less (Larkin and Quine, 1989).
- Bird echoes often exhibit an asymmetric reflectivity distribution.
- Bird echoes often show up in the same locale at the same time of day.
- Bird echoes exhibit a pattern where the maximum reflectivity is co-located with maximum velocity.
- Bird echoes are characterized by an arc pattern with a donut-shaped signature in the middle.
- Birds are typically confined to a narrower layer of the atmosphere than weather.

Many of these measurements and characteristics would be obtainable and observable with an ASR-9 with suitable signal processing. An example of the AUS ASR-9 WSP detecting a departing flock of birds is illustrated in Figure 3. The reflectivity is shown on the left, and the Doppler velocity is on the right. The range ring is at 10 km. The birds can be clearly seen as a solid 20 - 35 dBZ echo within the area delineated by the white rectangle. Note that there is a reflectivity minimum near the center of the echo region (A), which corresponds to the lack of targets near the departure origin. A reflectivity annulus pattern is a frequently observed signature associated with birds departing from a roost. In this case, the echo is elongated in a north-south direction and is primarily composed of targets moving away from the radar.

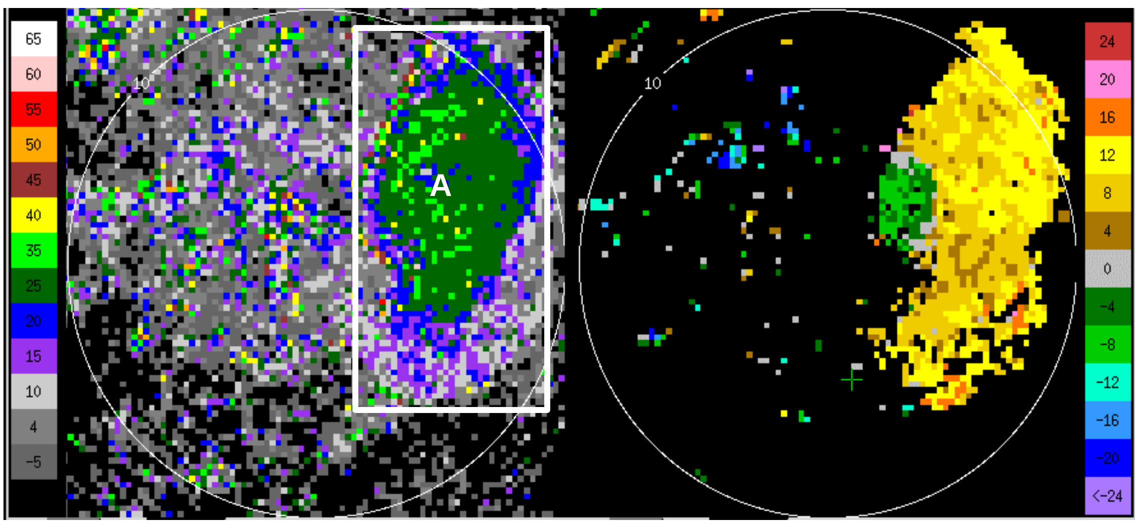

Figure 3. Reflectivity (left) and velocity data (right) for a bird event observed by the ASR-9 WSP at AUS. Range ring is at 10 km.

Bats and birds occupy a relatively low range of altitudes compared to weather. The dual broad-elevation fan beams utilized by the ASR-9 are offset by 3.5 degrees, providing a sufficient degree of altitude resolution to allow discrimination of low-altitude biological targets from more vertically distributed targets such as weather. The reflectivity difference between the two ASR-9 beams is often a useful discriminator. Figure 4 shows reflectivity images from low (left) and high (right) elevation beams of the ASR-9 WSP for an evening bat exodus event at AUS. These raw reflectivity data have not been subjected to clutter filtering or other data quality editing. The bats are departing from three distinct roost locations indicated by the white circles. The reflectivity from the bat echoes is considerably stronger in the low beam than in the high beam.

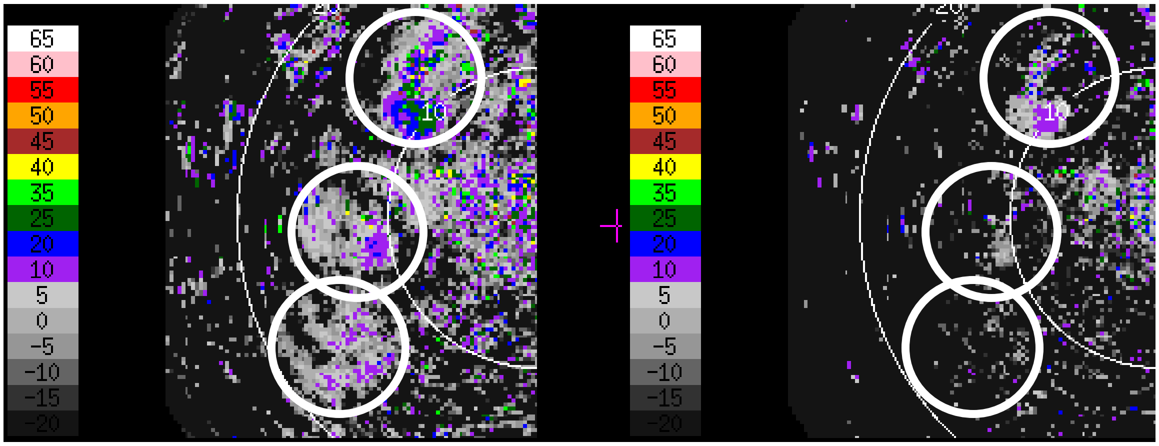

Figure 4. Raw (unedited) reflectivity images from the low (left) and high (right) beams of the ASR-9 WSP radar at AUS for a bat exodus event. The bats are departing from three distinct roost locations indicated by the white circles. Range rings are at 10 km intervals.

Motion is another useful indicator. The echo region associated with birds departing from roosts expands very quickly over a short time period. An analysis of several bird roost departures observed by the AUS ASR-9 WSP found that the leading edge of the bird echo region expanded at speeds of 10 to 13.5 m/s. The velocities of individual birds may be higher than this; speeds of 15 to 20 m/s are common.

6. Algorithm Overview

Figure 5 is a block diagram showing the processing flow of the automated bird detection algorithm currently under development at Lincoln Laboratory. The full set of ASR-9 WSP base data products are currently generated once every 12 scans (approximately 55 seconds), Since our initial algorithm implementation focuses on detection of moving flocks of birds, this update rate is probably sufficient. However, monitoring of small groups or individual birds will require updating and tracking at a more frequent interval. Reflectivity and Doppler velocity data, together with associated quality flags (indicating residual clutter, out-of-trip weather, and AP contamination) from the high and low receiving beams of the ASR-9 are input to a series of feature detectors. These feature detectors utilize an image pattern matching technique developed at Lincoln Laboratory called Functional Template Correlation (FTC) [Delanoy, 1993]. The FTC operation returns for each pixel location in the input image, the probability that the particular feature is present in the imagery. The resulting pixel map of probabilities is called an interest image. The interest images from each of the feature detectors are fused at the pixel level using a fuzzy weighted average to generate a combined interest image, representing the aggregate probability of the presence (or non-presence) of birds. The regions of bird echoes are then extracted by applying a threshold to the combined interest image. The extracted bird events are associated with prior detections to update the tracking history. The detections are then output to the user display. Relevant statistics for each detection are output to an associated database for later reference.

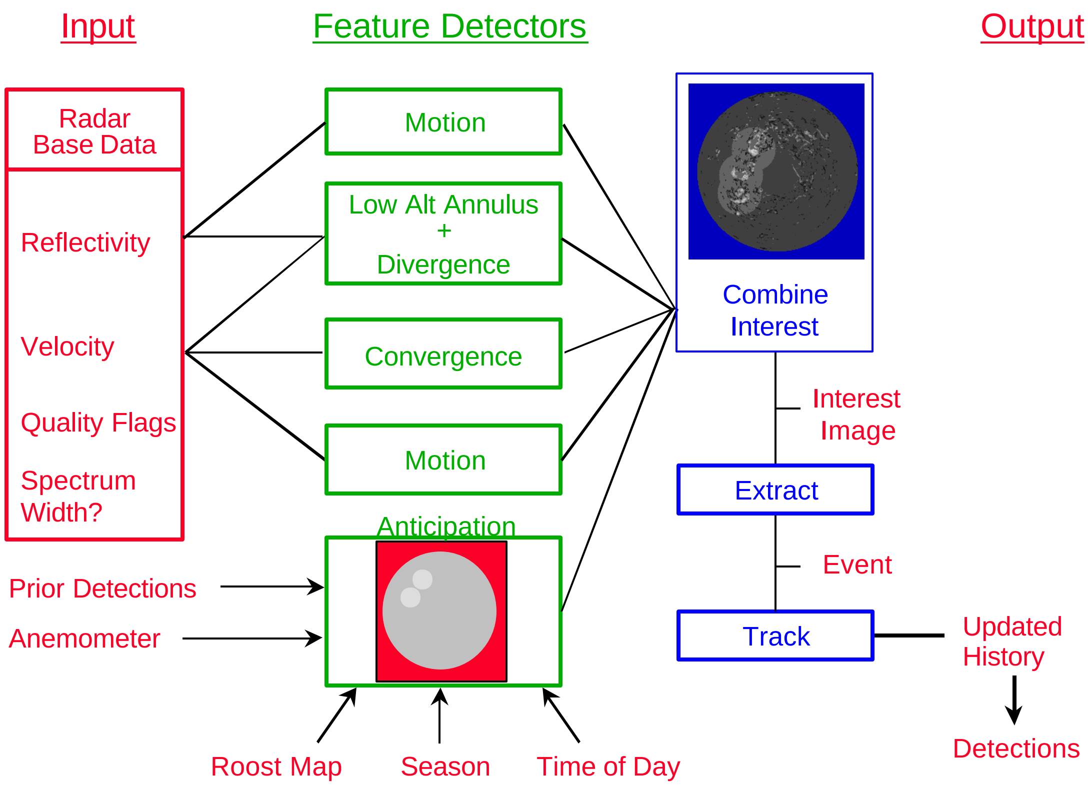

Figure 5. ASR-9 bird detection algorithm block diagram.

Anticipation plays a significant role in the detection process. An anticipation interest map is constructed from a variety of information sources including season, time of day, current weather conditions (e.g., winds and precipitation), roost locations, and prior detection locations. Thus, the anticipation interest map is used as a means of broadly adjusting overall algorithm sensitivity as well as selectively sensitizing the algorithm to regions where birds are currently being detected. By fusing the anticipation interest map with interest images from the feature detectors, the accumulated feature evidence can be further supported (or negated) based on situational context.

Figure 6 shows an analysis display from the initial TAHAS algorithm consisting of various images constructed during processing of a single scan of ASR-9 WSP data. The data are from an AUS bat roost exodus event that occurred on the evening of November 11, 1999. The bats began leaving their roosts approximately 25 minutes prior to the time shown in the figure shown. The top row shows WSP reflectivity images from the current and prior processing intervals (images labeled CURRENT REFL and PRIOR REFL). The difference of these two images is shown to the right (REFL MOT DIFF), and the motion interest image that results from FTC filtering of the difference image is shown in the last image on the right (REFL MOTION).

The second row shows the low-beam velocity (VELOCITY) from the WSP and associated derived images. The CLEANED VELOCITY image was computed by removing noisy velocities from low SNR regions in the low-beam velocity image and applying a spatial median filter. The VELOCITY STD DEV image is the variance of the low-beam velocity. Note that regions of bird/bat echoes exhibit low velocity variance (dark areas). The SHEAR image represents the local change in velocity computed along each radial of the CLEANED VELOCITY image. Runs of divergent velocity change have positive values (cool colors), while runs of convergent velocity change have negative values (warm colors). A line of divergence associated with the bat exodus is centered 10 km NW of the radar.

The third row illustrates the recognition of low altitude reflectivity echoes consistent with biological targets. The high beam reflectivity (HI-BEAM REFL) image is pixel-wise subtracted from the low beam reflectivity image (LO-BEAM REFL), and the resulting difference image (not shown) is input to the FTC filtering operation to produce the interest image on the far right (LOW-ALT REFL). Areas of clutter (flagged by the WSP processor) are shown in the CLUTTER image and are excluded from the interest map.

The bottom row summarizes the later processing stages. The left-most image is the ANTICIPATION interest image. Locally higher levels of anticipation interest are assigned in association with favored roost locations (the three overlapping circular regions), and areas of prior recent detections (brightest pixels). The COMBINED INTEREST image represents the weighted average of the feature detector interest images and the ANTICIPATION interest image. Regions of sufficient combined interest are extracted and smoothed (THRESHOLDED), and the corresponding areas in the CURRENT REFL image are mapped to a 6-level intensity scaled and displayed as the final product (DETECTIONS).

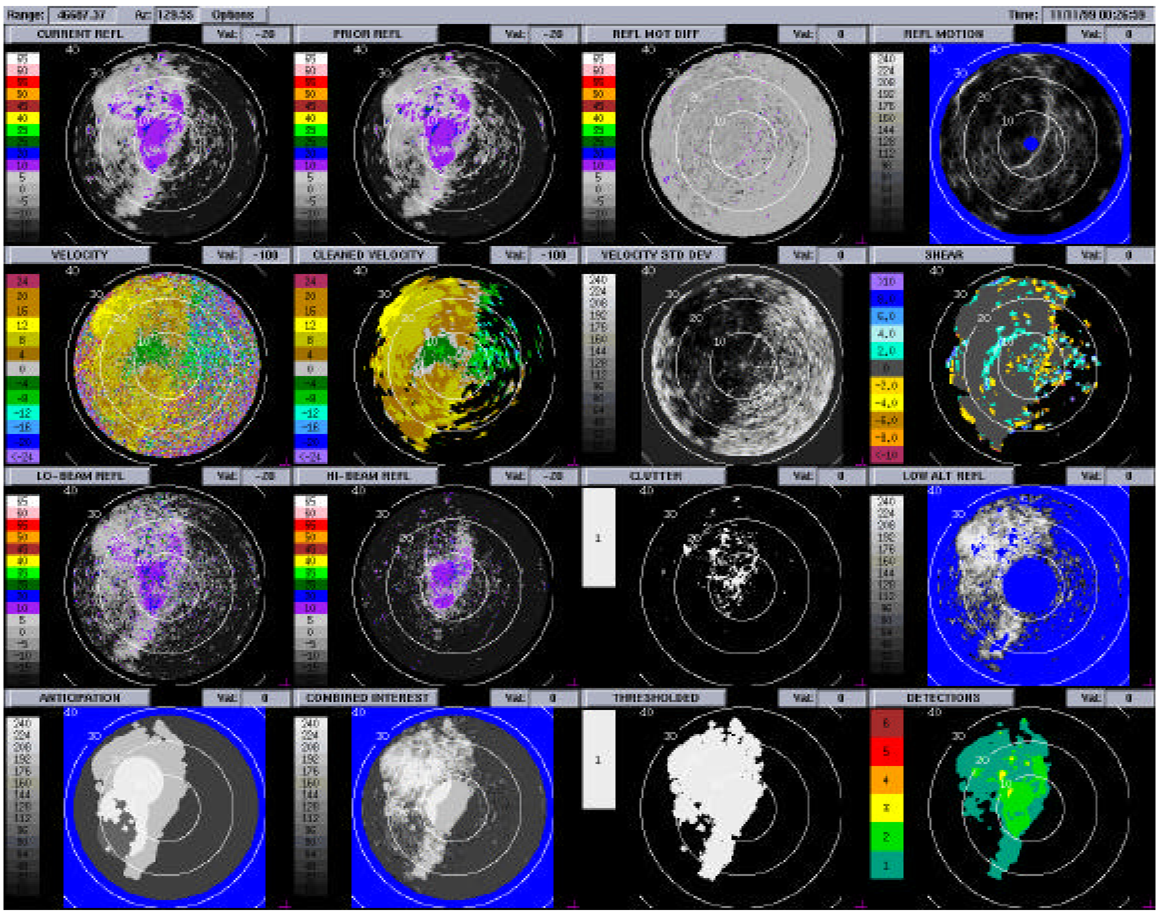

Figure 6. Analysis display for the Terminal Avian Hazard Advisory System (TAHAS).

As development and testing proceed, existing feature detectors will be refined and several new feature detectors will be added. Some additional planned feature detectors include:

- A roost divergence detector that recognizes the strong divergent velocity pattern associated with the initial phases of roost departure.
- A reflectivity annulus detector that generates interest for arc-shaped reflectivity regions with a central reflectivity "hole".
- A low velocity variance motion detector that generates confirming interest for moving regions of low velocity variance.

Thunderstorm gust fronts can produce low-altitude reflectivity thin line echoes that could be mistaken for birds. In order to avoid false alarms from this phenomenon, a reflectivity thin line echo detector originally developed for gust front detection may be incorporated into TAHAS and its interest map used in a negative fashion to suppress confirming interest that may be generated by the various bird feature detectors.

7. Conclusions

The ASR-9, with its high scan rate and on-airport siting, is well suited for bird detection. Many of the well-documented radar signatures of avian targets have been observed in ASR-9 data. At AUS, TX, where an ASR-9 WSP is in operation, bird and bat activity have been observed to trigger false wind shear alerts. An initial Terminal Avian Hazard Advisory System (TAHAS) has been developed to automatically detect flocks of bird in real-time using ASR-9 data. The detection algorithm uses state-of-the-art multi-dimensional image processing and data fusion techniques that have been utilized at Lincoln Laboratory for similar automatic target recognition problems.

While the initial algorithm implementation focuses on detection of flocks of birds, a full-fledged bird strike warning system needs to recognize smaller groups or isolated birds as well. The ASR-9 is designed for detection and tracking of isolated targets, so the issue with regard to detection of individual birds is whether or not radar cross-sections for birds are sufficiently large to be detected in the presence of noise and/or ground clutter. Using time-series I,Q data collected from the AUS ASR-9 WSP, we are presently exploring alternative ASR-9 signal processing approaches utilizing elements of algorithms currently implemented in the target channel processing of the ASR-9.

Time-series and base data from the Austin ASR-9 WSP will continue to be collected during periods of bird and bat activity. Where available, we envision that data from a pencil-beam TDWR would provide useful additional information to augment the processing of ASR-9 data to detect birds and bats. Information from the national AHAS database would also provide useful cueing information regarding the movements of large migratory flocks of birds.

Algorithm development continues with additional feature detectors being developed to make full use of the signatures evident in the radar data. We expect to have a preliminary assessment of algorithm performance completed by the end of summer, 2001.

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