Affordable, Real-Time, 3-D Avian Radar Networks For Centralized North American Bird Advisory Systems

Peter Weber, B.Eng, M.Eng, Sicom Systems Ltd.
Tim J. Nohara, B.Eng, M.Eng, Ph.D., PE, Sicom Systems Ltd.
Sidney Gauthreaux Jr., MS, Ph.D., Clemson University, Radar Ornithology Laboratory

Key Words: avian, radar, network, bird, tracking, detection, automated, strike, real-time, advisory, BASH, affordable, aircraft

ABSTRACT

Affordable avian radar systems are being developed for Natural Resource Management (NRM) and bird aircraft strike hazard (BASH) applications. Recently [1], the authors have reported on mobile avian radar system requirements and on a system design that is state-of-the-art. In the present paper, the system design of a single avian radar is expanded in scope to address 3-D avian radar networks. These are essential to fully realize an affordable yet high-performance North American bird advisory system. The proposed avian radar network design includes antenna, transceiver and signal processor designs for the avian radar sensor, network design, sensor integration, and system operation and control from an operations center.

1. INTRODUCTION

The BASH problem requires cost-effective, real-time detection and tracking of small maneuvering bird targets. Billions of dollars in damage and loss of life have been recorded because of aircraft flying into birds, particularly during take-off and landing in the vicinity of airports. An affordable network of real-time avian surveillance radar systems suitable for the bird strike problem is under development. This network is designed for real-time alerts and advisories, as well as for longer term studies of migratory patterns.

The operation of a single, short-range, avian radar system with real-time remote data access and control over a network (e.g. the Internet) has been demonstrated. Such a radar system specifically addresses the bird strike problem at or near the airfield (in the 0 to 6 nmi range). These radars would form an important component of an avian surveillance network. While more developmental and experimental work is needed to establish the performance characteristics of the avian radars, and to develop operating procedures for their use, the prospect of a high-performance, affordable radar surveillance network for bird strike avoidance is clearly within reach.

The paper is organized as follows. Section 2 provides a summary of recent avian radar work relating to the BASH and NRM applications and to bird strike advisory systems. This review supplies requirements and motivates a design approach for affordable, airport-based, 3D, avian radar networks. This design approach is presented in Section 3 (the sensor design) and Section 4 (the network design). The paper concludes with a discussion of future work needed to realize fully-operational systems.

2. BACKGROUND REVIEW

2.1 *BIRDRAD*

In 1998 a bird-detecting radar, called BIRDRAD, was developed by the Clemson University Radar Ornithology Laboratory (CUROL) for studying bird activity in areas where other radar coverage (e.g., WSR-88D and ASR radars) was absent or inadequate. The base unit is a Furuno 2155BB marine radar, but the T-bar antenna has been replaced with a 1-m parabolic antenna that can be adjusted to any angle between horizontal and vertical. A complete scan (i.e. a full revolution of the antenna) occurs every 2.5 seconds. Large birds and flocks of birds are readily detected out to a range of 6 nmi (11 km). Because of the narrow radar beam (2.5° in the original unit), precise three dimensional tracks of birds can be recorded over the full 360^{o}, allowing birds flying in any direction to be sampled and tracked. This approach has been favoured over the vertical scanning approach because it does not require birds to fly along a particular direction in order to be reliably tracked. The antenna and transmitter/receiver (T/R) units are mounted on a movable cart and the radar controls, GPS, computer and other support equipment for BIRDRAD are housed in a mobile trailer. Since 2000, six BIRDRAD units have been deployed at various U.S. Navy, Marine, and Air Force bases. These units have a 24 inch parabolic antenna (4.0°) beam width that allows greater atmospheric sampling but less spatial resolution of targets.

2.2 *WSR-88D*

The WSR-88D Doppler weather surveillance radar network in the United States contains approximately 150 radars. These very sensitive radars can easily detect birds, bats, and insects in the atmosphere, and are being used for studies of bird migration within 124 nmi (230 km) of the radar [2, 3] and nationwide [4]. The WSR-88D provides basic information on relative reflectivity, radial velocity, and spectrum width within pulse volumes defined by beam width (approximately 1°) and pulse lengths (1.57 and 4.5 microseconds or 0.24 or 0.68 km, respectively). The volume coverage patterns (scans at increasing elevation angles) differ between clear air and precipitation. The WSR-88D is typically used to measure bird

Presented at the Bird Strike 2005 Conference, August 14-18, 2005, Vancouver, B.C., Canada

targets between 500 to 15,000 feet above the ground surface. Procedures have been developed to process base reflectivity and base velocity products from the WSR-88D. Radial velocity aids in distinguishing birds from other airborne reflectors on the basis of air speeds. Bird data are extracted from WSR-88D images by subtracting pulse volumes that have a low probability of being birds based on air speeds [4,5]. The density of bird migration is measured in the remaining pulse volumes using a calibration curve based on direct visual observations [3].

At CUROL, WSR-88D data are being used for several projects that relate to the avoidance of bird/ aircraft collisions, flight safety, and conservation of migratory birds [6]. The data are being used to delimit important migration stopover areas within 60 nmi of the radar station. This is possible because shortly after takeoff, concentrations of migrants can be detected by the WSR-88D and related to source areas on the ground. Classified satellite imagery is then used to identify the habitat type of the migration stopover areas. CUROL is also using WSR-88D data to characterize the seasonal temporal patterns of bird migration, and the day-to-day variation in migration density is being related to weather variables for the development of location-specific statistical forecast models of bird migration. These models are designed to use forecast weather variables so that flight operations or BASH personnel can forecast the bird migration density at least 24 hours in advance. The WSR-88D data are also being used at CUROL to generate bird migration maps for the continental U.S.. Four maps covering four different altitudinal zones show the peak density of migration for each station for each day during the spring and fall migration periods. As these maps are generated over multiple years, they will prove to be an extremely valuable resource for flight operations planning, and the improvement and enhancement of the Bird Avoidance Models (BAM) and the Avian Hazards Advisory System (AHAS).

2.3 *ASR-9*

The ASR-9 is an airport surveillance radar that applies Doppler processing of signals from dual broad-elevation fan beams together with a rapid antenna scan rate to provide high-update, wide-area surveillance of aircraft out to an operational range of 60 nmi. The ASR-9's parameters make it suitable for both weather and bird detection. A recently deployed Weather Systems Processor (WSP) enhancement at 34 ASR-9 equipped airports across the US provides a separate high-sensitivity receive path and appropriate signal processing to generate high-quality reflectivity and Doppler velocity base data products that can be used by automated weather and biological target detection algorithms.

Bird and bat flocks are less distributed vertically than weather. The ASR-9 provides a sufficient degree of altitude resolution to allow discrimination of low-altitude biological targets from more vertically distributed weather targets. The reflectivity difference between the two beams is therefore a useful discriminator. Motion is another useful indicator of bird flocks. The echo area associated with birds departing from roosts expands relatively quickly over a short time period. By differencing a prior reflectivity image from the current reflectivity image, the leading edges of the expansion can be seen as lines of positive reflectivity difference. Detection and tracking of individual or small groups of birds has also been achieved by accumulating scan-to-scan differences of the high update (5 second) low reflectivity signals and using pattern matching filters to extract the resulting "trails" that are produced in the cumulative difference images [7].

2.4 *Efforts to Classify Birds Using Radar*

Small marine navigation radars are useful for detecting and monitoring bird movements within a few kilometers of the radar, but trying to identify the type of bird solely from the characteristics of an echo on the display of the radar is problematical. An echo from a flock of small birds may appear very similar to an echo from a single large bird, and echoes from large insects may appear very similar to those produced by small slow flying songbirds. The position of a bird target in the radar beam is another important factor that influences its radar echo. If it is sampled at the centre of the beam, it will produce a much stronger echo (typically 6 dB or 4 times as strong) than if it is sampled at the beam edge (for the usual case of overlapping beams occurring at ½ power points of the beam pattern). The same bird sampled at a range of 4 km will produce an echo 24 dB weaker (i.e. less than $1/100^{th}$ the strength) than if it was sampled at a range of 1 km. Furthermore, the spatial extent of the echo varies linearly with target range, to first order. Finally, the aspect (alignment and orientation) of a bird's body in the radar beam also greatly influences the characteristics of its echo on the radar display.

Numerous studies of bird movements with marine surveillance radars have attempted to correlate echo characteristics with visually identified birds with little success. Although Harmata et al [8] could not determine species from the characteristics of echoes, they subjectively assigned identifications to several groups (e.g., waterfowl, raptors, small passerines) on the basis of the characteristics of echoes produced by visually identified birds during daylight monitoring. Signature behavior and speed also were used to help identification. It should be stressed that echo speeds on surveillance radars are ground speeds and in order to use speed for target identification air speeds should be used. Air speeds and flight direction can be computed if information on wind velocity and direction at the altitude of the target is known. More recently Sjoerd Dirksen of Bureau Waardenburg in the Netherlands has correlated visually identified birds with the characteristics of corresponding echoes on radar displays of marine radar. Although many hundreds of data points have been gathered to date in this effort, the correlation between echo characteristics and bird species is not significant [9]. Although narrow beam tracking radars have been used to examine wing beat signatures in an attempt to categorize the identity of the birds responsible for echoes [10, 11], targets are not in the beam of a marine surveillance radar long enough to measure variation in reflectivity attributable to wing beat patterns.

2.5 *North American Bird Strike Advisory System*

A strategic plan for a North American Bird Strike Advisory System has been developed [12]. Using radar systems to detect birds is a key component of the plan. The following are some of the ideas and recommendations within the plan that are relevant to this paper:

- Provide a centralized wide-scale advisory system
- detect birds beyond the airfield
- provide real-time and widely available advisories (web-based)
- reliably distinguish dangerous birds from non-dangerous ones
- use short-range avian radars for 3-D coverage out to 6 nmi and to 3000 ft above ground level
- use available airport surveillance radars and weather radars for greater coverage; ASR-9 for 6 to 60 nmi, WSR-88D for 10 to 124 nmi
- use both real-time and historical information
- work includes research, development, test and implementation of radar systems, airport bird strike risk warning systems, and wider-scale bird strike advisory systems
- intermediate goals include the development of real-time detection and tracking systems, of bird strike risk assessment modules, and of airport-level bird strike advisory systems

3. AIRPORT-BASED AVIAN RADAR SENSOR DESIGN

3.1 *Avian Radar Sensor Design*

The design of a state-of-the-art, short-range avian radar for use at airports is considered in this section.

The radar scans a local volume above and surrounding the airfield; typical coverage is 0 to 6 nmi range, 360^{O} azimuth, 0 to 3000 ft height. The sensor concept is flexible in terms of radar frequency, beam shape, scanning pattern, etc. These sensor systems are made affordable by integrating commercially-available off-the-shelf (COTS) marine radar transceivers and antennas with personal computer (PC)-based radar processors employing high-performance, custom-developed radar processing software These sensors are mounted on or near the ground, and are thus easily movable. They can operate unattended 24/7 in an airfield environment.

While coherent radar technology used in systems such as ASR-9 or WSR-88D could be reconfigured to meet short-range avian radar requirements, resultant systems would be prohibitively more expensive.

Standard marine radar antennas (e.g. 6-foot T-bar antenna) provide high-gain, good azimuth resolution and elevation coverage, but poor elevation resolution because of the fan beam shape. Parabolic dish antennas (with pencil beams), on the other hand, reduce elevation coverage in favor of better elevation (height) resolution. The dish antenna can be inclined in elevation either to match the volume coverage needed during take-off and landing (typically 5° to 10°), or for sampling bird migration (as high as 30^{o}).

An ideal avian radar antenna would provide good elevation coverage as well as good elevation accuracy, in addition to good azimuth resolution (as already afforded by COTS horizontally scanning antennas). While a 2D phased array antenna could satisfy these requirements, it would be prohibitively expensive to consider any further. On the other hand, the required capability could likely be realized cost-effectively using an appropriately designed, horizontally scanning, elevation monopulse or sequential lobing antenna. Alternatively, a horizontally scanning antenna with limited vertical scanning (mechanically or electronically) could provide a viable trade-off between volume coverage and target height accuracy for 3D avian radars. Developing a suitable antenna should be a top priority for all parties interested in BASH, NRM and bird advisory systems.

The avian radar sensor proposed here involves a modular, software-definable radar approach that allows one to interface, in a cost-effective manner, the radar processor to a wide range of antennas, including COTS marine radar ones, dishes, as well as the aforementioned future antennas. This modular approach is necessary so that complete radar processor redevelopment is not needed when the ideal antenna becomes available. It also supports a number of lower-cost avian radar sensor options for use in applications where full 3D target tracking is not an essential requirement.

The avian radar must be capable of detecting and tracking hundreds or thousands of birds (and aircraft) locally in real-time. Track filters should be parametric in nature (e.g. extended Kalman filtering) so that target dynamics can be predicted reliably into the future (necessary for BASH). For each track, the sensor should determine, maintain and update position (3-D), velocity (speed & heading), and reflectivity (e.g. intensity, echo size) and track quality metrics. Using these data (and their progress over time), the sensor (or some remote data processing application) could (ultimately) classify whether tracks are dangerous or not. Tracks and bird densities are displayed on a local GIS map in real-time. The radar sensor can also send tracks, densities, local advisories, etc. onto a network in real-time.

State-of-the-art avian radars are designed to provide continuous, day-or-night, all-weather, local and wide-area situational awareness with automated detection, localization and warnings of hazards. They are also designed to be part of a network of radars operating together to provide a composite picture as the basis for a regional, national or continental advisory system. Because of the need for automated warnings, they must provide high-quality target track data with sophisticated criteria to determine potentially dangerous target behavior, as well as real-time communication of alerts to users who require that information. Avian radar sensors are also designed to minimize operator interaction.

In summary, ideal, avian radar sensors provide or support:

- Low-cost, high-performance radar antennas and transceivers that can be mounted on land-based platforms as well as on mobile vehicles
- Radar processing that can reliably detect and track small, low-RCS (radar cross section), maneuvering bird targets as well as aircraft targets in dense target and clutter environments
- real-time, 3-D coverage out to 6 nmi, 3000 ft
- real-time and continuous target data storage into flexible, high-performance database for subsequent and concurrent retrieval by multiple remote users
- Automatic hazard detection and alert capability to remote users
- The formation of radar networks to provide wide-area coverage
- Low cost of operation through remote access and control
- Low life cycle costs
- Flexibility and interoperability through use of Web Services and Standard Network Protocols
- Data and analysis support for research and development

3.2 *Example Avian Radar System*

The U.S. Navy's *eBIRDRAD* avian radar system described in [1] is an example of a state-of-the-art avian radar that presently satisfies many of the design characteristics described in Section 3.1. SPAWAR Systems Center, San Diego undertook the development of this system through a contract to Computer Sciences Corporation and its subcontractor Sicom Systems Ltd., with financial support from the NAVFAC Environmental RDT&E. A review of its performance during bird migration provides solid verification that fully operational, inexpensive, high-performance, avian radar sensors and networks are indeed within reach.

The radar transceiver is a COTS, noncoherent, marine radar, and the antenna employed is a two foot parabolic dish with a 4^{O} beamwidth. With its 50 kW peak power at X-band, and range resolution on the order of 10 m, it is well-suited for detecting and localizing birds in the 0 to 6 nmi range.

The eBIRDRAD system uses the Accipiter™AR Radar Processor (www.accipiterradar.com) developed by Sicom Systems Ltd. The Radar Processor includes a digital radar interface board mounted in an off-the-shelf PC. The radar interface digitizes each raw radar sweep and provides the data to the software-definable radar processor, which carries out the radar signal processing, display, detection, tracking, data archiving and distribution. The radar processor includes functions such as scan-conversion, adaptive clutter-map processing to remove ground and weather clutter, detection, and numerous operator displays. The processor is highly modular in design, implemented in C++, and is controlled by a single, sophisticated, completely integrated client application suited for avian radar processing. It efficiently implements all radar processor functions in software in real-time. A special bird-trails mode has been developed that retains current and past bird echoes and presents them as a fading trail, in order to make bird radar signatures easily visible to an operator. Low detection thresholds are used, in order to increase the sensitivity of the radar. Since the use of low thresholds causes the false alarm rate to increase substantially, the radar processor includes high-performance tracking algorithms as described in [13]. An experimental configuration of eBIRDRAD is shown in Figure 1. Some recent experimental results were obtained with eBIRDRAD during night-time migration at NAS Patuxent River in Maryland in May 2005. The results are very encouraging. When adaptive clutter suppression is used to suppress ground clutter, residual radar echoes due to moving targets such as birds, ground vehicles, and aircraft survive. In Figure 2, the PPI display is shown during evening migration on 9 May 2005. Bird targets are easily identified as a result of the trails processing algorithm that displays echoes from the current scan in one color (yellow), and echoes from previous scans in a second color (blue) that fades with time. The antenna was tilted up 20^{o} to sample higher altitude birds. The largely northeasterly migration of numerous birds is easily discerned from the display.

If automatic detection and tracking algorithms are applied, Figure 3 results. Tracks are indicated by a square symbol (drawn at a target's current position) with a line emanating from the square (pointed to the direction the target is heading). This real-time operator's display, where target data are overlaid onto a facility map, enables target behavior to be more easily understood and communicated.

Figure 1: Experimental radar configuration.

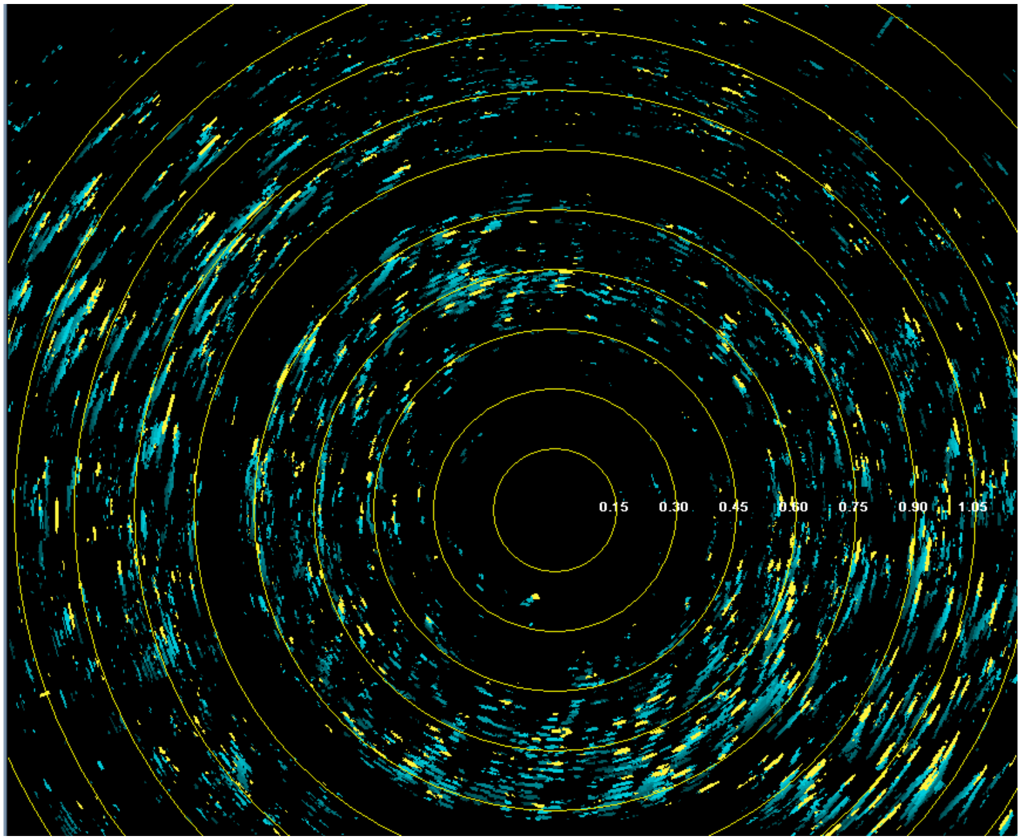

Figure 2: Operator's PPI display during night-time migration on 9 May 2005 in bird trails mode.

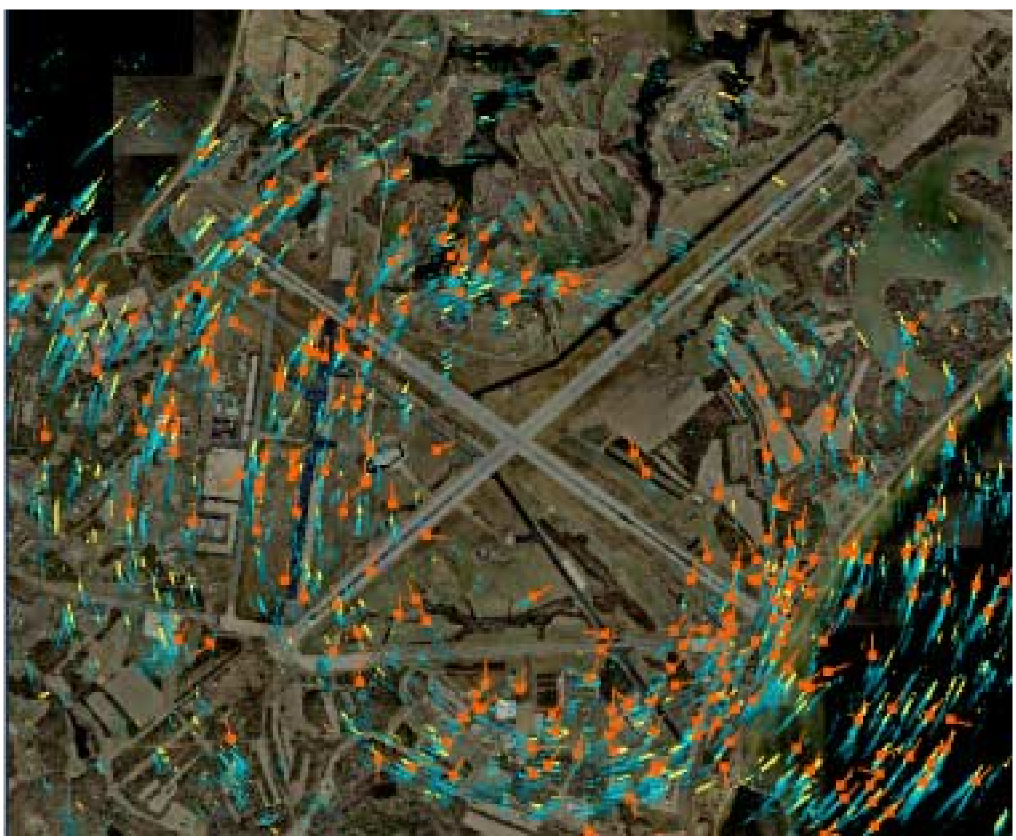
Figure 3: Operator's display at same time with bird target tracks overlaid on base map.

4. AVIAN RADAR NETWORK DESIGN

Avian radar networks and centralized wide-scale bird strike advisory systems have the following requirements:

- data (tracks, displays, alerts and advisories) sent to local users (remote from the operations center) in real-time
- data sent to operations center (in real-time if needed) for regional/national/continental advisory purposes; information from multiple sensors is integrated there
- data can be remotely accessed (queried) in real-time
- archived data can be remotely accessed
- support for Internet Web services
- user-friendly, widely-available dissemination of information
- sensors remotely controlled and scheduled (at airfield or by operations center)
- "real-time information and predictions available on user-friendly web-based maps at North American, national, regional and local levels" [12]

The aforementioned network and advisory system requirements lead to several additional design considerations over those described in Section 3.1. Taking a top-down design approach, consider the radar network architecture illustrated in Figure 4.

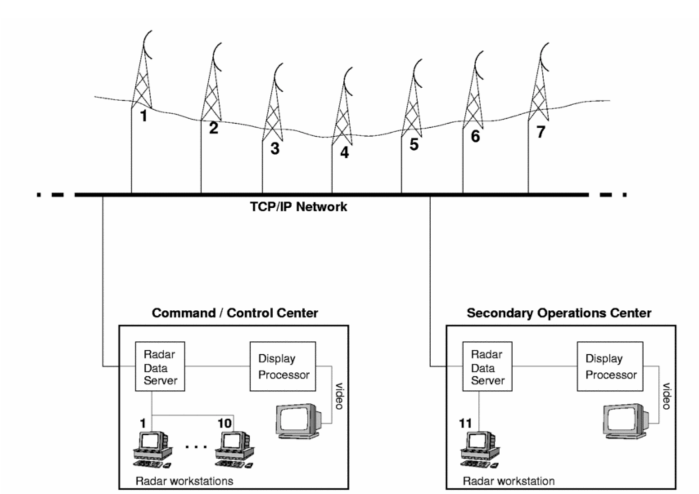

Figure 4: Proposed Radar Network Architecture

Several airfield avian radars (and indeed other radars such as ASR-9s and WSR-88Ds) are shown networked to an operations or command/control center. The avian radar's wide-area network design uses open Web services and network protocols such as TCP/IP and HTTP. It can thus exploit COTS network technology to affordably configure arbitrary, secure networks almost anywhere. This includes wireless networks and the Internet. This architecture seamlessly provides for regional, national and continental bird strike advisory systems.

Multiple user support is provided by a client/server model with Web Services. The Web Services could be hosted either through the Radar Data Server (Figure 4 and 5) at the command/control center, or through a secondary operations center, for example. The Radar Data Server is designed to receive radar data from the various radar sensors in real-time, continuously store the data, and serve the data to authorized clients. This approach enables customized user applications to be easily developed and integrated. Many different services can be provided simultaneously to many users. The system is easy to adapt. Users can develop their own services. Such a model is ideal for researchers and is necessary in order to cost-effectively and incrementally improve the system following an initial launch.

Support for multiple sensors is achieved via asynchronous connections between the sensors and the operations center. This is an affordable, flexible approach, which allows different sensors to be added to the system independently, and can exploit the Internet. In Figure 5, the radar network interface between a given avian radar sensor and the Radar Data Server is illustrated.

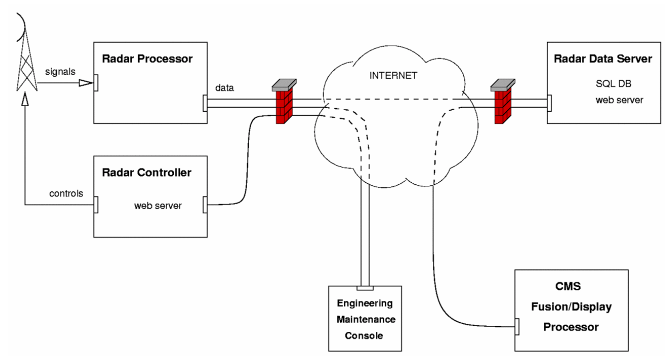

Figure 5: Radar Network Interface Diagram

The Radar Processor provides track reports that are rich with target attributes and that are available in real-time to remote users. These reports are continuously streamed to a high-performance SQL database used for archival as well as for remote communication with user applications. The SQL database is hosted on the Radar Data Server, which can be located at the operations center (Figure 4) or locally (e.g. for the case of a single radar or a local radar network). Each track report contains target information such as position, speed, heading, track stage, track uncertainty, echo size and intensity, etc. These target attributes can be used for the study and classification of targets of interest, and for multi-sensor fusion at the operations center.

Because (typically) track data are communicated, as opposed to raw radar data, having enough network bandwidth is not a risk, even for dense target scenarios. Since the track reports contain all of the important target data (date, time, position, dynamics, size), remote situational awareness for BASH and NRM applications is easily realized. For cases where raw radar data distribution is desirable, real-time distribution could be handled through dedicated, high-speed networks, or more likely, non-real-time distribution could be supported.

User applications, typified in Figure 5 by the CMS (Central Monitoring Site) Fusion/Display Processor, talk to the Radar Data Server in order to retrieve the required target data. Such applications include simple, real-time radar display applications run by multiple remote users at their respective locations. Another more complex application would be a sophisticated multi-sensor fusion processor run at an operations center in order to create a composite, North American picture. User applications are preferably designed as Web Services.

Each radar processor can be remotely controlled from an Engineering Maintenance Console located anywhere on the network, using COTS software (e.g. virtual network server and client software or Web Services). From a usability and operational cost standpoint, as well as to support automated scheduling of operation, it is imperative that the radar transceiver can also be operated remotely over the network, ideally using a Web Service. Features such as power-on/off, transmit/standby, and waveform selection require remote control. While such remote control features are not available today from marine radar transceiver manufacturers, they can indeed be developed. The eBIRDRAD system, for example, has integrated an Accipiter™ Radar Controller developed by Sicom Systems Ltd., specifically for this purpose.

The avian radar sensor designs discussed in section 3.1, combined with the networking design extensions described in the current section, support affordable, state-of-the-art avian radar networks for centralized, North American Bird Strike Advisory Systems.

5. FUTURE WORK

In this section, we briefly summarize some areas relating to avian radars and networks where further research and development are needed.

5.1 *Improved Antenna Designs for Avian Radars*

The antennas used in avian radars can be improved in two ways: with lower sidelobes, and with localization of targets in elevation while not overly sacrificing volume coverage. Lower sidelobes will help increase the probability of detecting birds in those spatial regions where residual sidelobe clutter is high.

5.2 *Classification of Target Tracks*

The ability to 1) distinguish types of targets (birds, or insects or aircraft), 2) identify types of birds, and 3) determine flock sizes is an important goal for future research and development of bird-tracking marine radars. Although one cannot currently, reliably classify birds, the rich target information provided from bird tracking radars such as eBIRDRAD may provide the detailed information on individually tracked birds necessary for the development of classification algorithms. Three-dimensional data on each track is essential for this task.

If reliable classification algorithms are to be developed, then avian radar systems should be researcher-friendly. This means that these systems should provide, in an open and practical manner, geo-referenced target data (i.e. complete detection data and track data), and free or inexpensive tools for researchers to easily access that data, review that data, and develop their own models and algorithms for testing with that data. Such features will allow researchers to publish and share their results, and to collaborate with each other. The results of these efforts will lead to the development of automatic or operator-assisted classifiers in affordable avian radars.

5.3 *Experimental Campaign*

An extensive experimental campaign is needed to rigorously evaluate the performance of avian radars. This includes reporting to and interaction with the user and research communities. The availability of automated scheduling over networks facilitates such a campaign.

5.4 *Information Integration and Fusion*

In order to provide centralized wide-area advisory systems, multiple sources of information (e.g. current weather and historical bird migration patterns with real-time radar data) needs to be integrated. This includes the integration, fusion and overlay of data from multiple sensors. These sensors can be of differing types (e.g. avian, WSR-88D, ASR-9).

General techniques for doing so are well-known to those skilled in the art. The concurrent availability of the multiple data sources is needed in order to research, develop and implement fusion techniques specifically suited to bird strike advisory systems.

5.5 *Network Development*

GIS and Web services applications for dissemination of radar data to user and research communities need to be developed. This process will naturally accelerate as more avian radars come on-line, and users become aware of the usefulness of the data.

5.6 *Bird Strike Advisories*

Information from a network of bird-tracking radars such as eBIRDRAD could be used via the Internet not only for real-time monitoring of bird movements (as is the case for the network of WSR-88D radars), but the data gathered from these radars could be used to develop statistical forecast models and advisories that predict specific and general bird movements (e.g., local raptor soaring activity, roosting movements of herons, dense bird migration) at a local, regional, and continental scale. Over time as data from the network is accumulated, one could develop an interactive atlas of bird migration on the Internet showing timing (daily and seasonal) and spatial (geographic and altitudinal) patterns for different types of birds. Such an atlas would be indispensable for planning flight operations and for resource managers interested in the conservation of migratory birds.

5.7 *Avian Processing on Weather or ATC radars*

Much of the avian radar processing (e.g. detection and tracking) could be applied to returns from weather radars or ASRs if we could access their digitized raw data stream. Because these radars are coherent, more reliable detection in clutter is achievable, as is more accurate estimation of target velocities.

6. SUMMARY AND CONCLUSIONS

Avian radar systems have been fielded that detect and track birds in the vicinity of an airfield. These systems are network-enabled, so that the information they gather can be stored continuously and distributed to remote users. Avian surveillance networks are being developed that link the avian radars together with other sources of information, including real-time (e.g. ASR-9 and WSR-88D), near real-time (e.g. weather conditions), and historical ones. These networks will facilitate the deployment of affordable bird strike advisory systems in the near future. Such systems should help greatly in understanding bird behavior and in increasing aviation safety across North America.

REFERENCES

[1] T. Nohara, P. Weber, A. Premji, C. Krasnor, S. Gauthreaux, M. Brand and G. Key, “Affordable Avian Radar Surveillance Systems For Natural Resource Management And BASH Applications”, IEEE Radar Conference, Arlington, Virginia, May 9-12, 2005.

[2] S. Gauthreaux Jr and C. Belser, "Displays of Bird Movements on the WSR-88D:Patterns and Quantification", Weather and Forecasting 13:453-464, 1998.

[3] S. Gauthreaux Jr and C. Belser, “Reply” to displays of bird movements on the WSR-88D: Patterns and quantification", Weather and Forecasting 14:1041-1042, 1999

[4] S. Gauthreaux Jr, C. Belser and D. Van Blaricom, "Using a network of WSR88-D weather surveillance radars to define patterns of bird migration at large spatial scales", In: Berthold, P., E. Gwinner, and E. Sonnenschein (eds.) Avian Migration. Pp. 335-346. Springer-Verlag, Germany, 2003.

[5] S. Gauthreaux Jr and C. Belser, "Bird movements on Doppler weather surveillance radar", Birding 35 (6):616-628, 2003.

[6] S. Gauthreaux Jr and C. Belser, “Overview: Radar ornithology and biological conservation.”, Auk 120(2):266-277, 2003.

[7] S. Troxel, “Progress Report on Development of a Terminal Area Bird Detection and Monitoring System Using the ASR-9”, MIT Lincoln Laboratory, Abstracts of 4th Joint Meeting Bird Strike Committee USA/Canada, October, 2002.

[8] A. Harmata, K. Podruzny, J. Zelenak and M. Morrison, "Using marine navigation radar to study bird movements and impact assessment", Wildlife Society Bulletin 27 (1): 44-52, 1999.

[9] S. Dirksen, "Paper delivered at the Collaborative Offshore Wind Research into the Environment Workshop at QintiQ site, Malvern Technology Centre, Great Malvern, Worcestershire, England", 4-6 April, 2005.

[10] B.Renevey, "Study of the wing-beat frequency of night-migrating birds with a tracking radar", Revue Suisse de Zoologie 88: 875-886, 1981.

[11] F. Liechti, "Paper delivered at the Collaborative Offshore Wind Research into the Environment Workshop at QintiQ site, Malvern Technology Centre, Great Malvern, Worcestershire, England". 4-6 April, 2005.

[12] R. DeFusco, M. Hovan, J. Harper, K. Heppard, “North American Bird Strike Advisory System Strategic Plan”, Draft Version 13, January 28, 2005.

[13] P. Weber, A. Premji, T. Nohara and C. Krasnor, “Low-Cost Radar Surveillance of Inland Waterways for Homeland Security Applications”, IEEE Radar Conference, Philadelphia, Pennsylvania, April 26-29, 2004.