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An Overview of Avian Radar Developments – Past, Present and Future

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ABSTRACT

For several decades, ornithologists and biologists have used radars to characterize the presence and movements of birds and other biological airborne targets. X-band and S-band marine radar transceivers have been successfully operated for applications such as natural resource management (NRM), environmental impact assessments (EIA), and bird aircraft strike hazard (BASH) management. In the past several years, numerous advances have been introduced into the marketplace, with others on the way, bringing with them many potential benefits. These include:

- performance improvements,
- continuous target data recording,
- analysis and visualization automation,
- remote and unattended operation,
- automated alerts,
- wide-area coverage,
- centralized target data collection,
- multi-sensor fusion,
- real-time target data distribution to remote users, and
- real-time integration into third-party situational awareness applications and Internet-based applications.

The objective of this paper is to stand back and take an organized look at these developments in avian radar technology, with a view towards improving our understanding of this complex tool set. By reviewing the past, a context will be provided within which one can better appreciate what has been accomplished in the present, and where technology and products still need to go in the future. It is hoped that a better understanding will assist stakeholders in making the best use of these tools, today and tomorrow.

1. INTRODUCTION

The BASH management problem requires cost-effective, real-time (subject only to a small latency), 3D tracking of small, maneuvering bird targets and aircraft over a comparably large surveillance volume. Airport-based avian radar systems that address BASH management requirements are the subject of this paper, since they will be capable of addressing NRM and EIA applications as well. ASR-9 Doppler airport surveillance radars and WSR-88D Doppler weather surveillance radars, while designed for specific, mission critical applications, have also been used for bird target detection over ranges of 60 nmi and 124 nmi, respectively [Weber et al., 2005, Larkin 2005]. For a number of reasons including cost, coverage, update rate, resolution, inaccessibility and interoperability challenges, these large aircraft surveillance and weather radar systems do not provide the fine, local bird target tracking information needed for BASH management at airports. As a result, the focus of this paper is on small, airport-based, avian radar systems that exploit inexpensive X-band and S-band marine radar transceivers and that have been developed specifically to track birds and planes. In the sequel, these radars will be referred to simply as avian radars since, unlike the ASR-9 and WSR-88D, birds are their primary focus.

Over the past 40 years, avian radar systems have been the subject of research, development, and use by researchers and consultants (biologists and ornithologists). In the late 1990s, commercially-available avian radar systems were introduced to the marketplace by some of these players. In the less than ten years since then, development has accelerated, as radar companies have entered the market in direct response to the growing awareness of the bird strike problem and the need for affordable avian radar solutions.

The paper is organized as follows. Section 2 provides a summary of key avian radar system requirements motivated by the BASH management application. This is followed by a straw-man design of an avian radar system that addresses these requirements. This design provides the functional context needed to understand the developments in avian radar, past and present, and those to come in the future. Section 3 provides a discussion of past developments along with the present state-of-the-art. Section 4 then contemplates expected future developments. Finally, Section 5 provides a summary and conclusions.

2. *AIRPORT-BASED 3D AVIAN RADAR DESIGN*

Requirements and a straw-man design for avian radar systems suitable for BASH management are described in this section.

2.1 *System Requirements*

A summary of desirable, high-level requirements for avian radars are listed below:

- **Real-time 3D bird and aircraft** target **tracking** throughout the radar coverage volume
- Integrated, **real-time** geographical information system (**GIS**) to place targets in earth coordinates
- Real-time **operator displays** at local and **remote** locations
- **Real-time alerts** of hazards
- **24/7 target data storage** suitable for complete replay and analysis in support of incident investigations, wildlife management processes, and system validation
- **Real-time streaming of target data** over network links with modest bandwidth, including the Internet, to a remote radar data server (RDS)
- Real-time support for **multiple remote analyst workstations (clients)** to receive and process target data for specific user missions / applications
- **Rapid replay of** stored **target data**
- **Automated radar system scheduler**
- Real-time **interfaces** for providing **target data** to **third party applications**
- **Multiple radar fusion** in support of a common operating picture (COP)
- Integrated **Real-time Target Classification (TC) Processor**
- Integrated **Statistical Avian Radar Data (SARD) Processor** in support of centralized hazard advisories with Web services
- **Multi-sensor integration** (e.g. cueing cameras, bird deterrent devices, acoustics for identification, automatic identification systems (AIS), integration with ASR-9 and WSR-88D target data, etc)
- **Electromagnetic compatibility** with other airport RF systems
- **Affordable/maintainable**

2.2 *Radar System Design and Concept of Operation*

Figure 1 illustrates an avian radar system design that satisfies the requirements described in Section 2.1. The design and concept of its operation are described here.

Since larger airports typically require more than one radar to satisfy coverage requirements, several radar nodes are shown in Figure 1, along with a break-out of one of them. Each node is a stand-alone avian radar consisting of a radar sensor/transceiver (RST) mounted on a platform, a digital radar processor (DRP), and a radar remote controller (RRC). The RST includes at least one scanner/antenna and corresponding transceiver(s). The RRC and DRP are connected over a network via TCP/IP. For affordability, reliability, and electromagnetic compatibility, the RST exploits commercial-off-the-shelf (COTS) X-band marine radar scanners and transceivers to the extent possible. This also permits flexibility in the choice of RST model to suit the mission and budget. The RRC provides a network interface to the RST so that it can be turned on/off and configured remotely by a radar technician, avoiding site visits. The DRP is also connected to a TCP/IP network for remote operation and remote video display (intended for the radar technician), and for target data distribution.

The RST is responsible for defining the surveillance or scanning pattern in the coverage volume, and for setting the physical limits on range, azimuth (horizontal) and elevation (vertical) resolution. In order to satisfy the 3D bird and aircraft target tracking requirement throughout the coverage volume (typically 0 to 6 nmi, 360 degrees, and 3,000' above ground level (AGL)), reliable position and height estimates of targets are needed. These requirements translate to an RST with the following characteristics:

- it scans horizontally to provide 360 deg coverage
- it has sufficient vertical coverage
- it has sufficient vertical resolution to produce reliable height estimates.

It should be noted that COTS marine radar array antennas cannot satisfy the BASH-driven 3D bird and aircraft target tracking requirement (as discussed in Sections 3.4 and 4.2 below). They do nevertheless provide useful 2D target tracking.

The DRP interfaces to the RST through a (internal) digital radar interface and is responsible for all real-time radar signal, data, and display processing including:

- signal processing
- detection processing
- track processing
- display processing
- GIS processing
- graphical user interfaces:
    - local GUI
    - remote desktop for remote control and remote viewing of DRP display
- 24/7 local target data recording
- target data streaming over a network to an RDS
- external interfaces to scheduler, health monitoring or other applications

Signal processing refers to the various stages of range and azimuth filtering applied to the digitized, raw radar echo signal before further processing. Detection processing is carried out on each scan (i.e. each revolution of the radar which typically revolves at 24 RPM or once every 2.5 seconds) of radar echoes. Its purpose is to <u>automatically</u>

detect all echoes that are potentially from real targets. Each detection includes a time-stamp, a position, an intensity value, and a height estimate. An unavoidable consequence of detection processing is that some detections will result from noise, clutter, and other interference. A real detectable target, however, will have a series of related detections occurring over a number of scans while the target remains in the coverage volume of the radar. A track processor is then needed to automatically associate or *connect the dots* (each detection being a dot) so that tracks are formed for each real target. Given that many detections observed over time are false alarms (i.e. not from real targets), and that there are often many targets grouped together, separating, crossing and maneuvering, automatic multi-target tracking is undoubtedly the most sophisticated and complex part of the DRP. Target tracking is a critical step in the processing and radar engineers have spent careers on this single aspect of radar processing. Ideally, GIS transformations are applied during the track processing so that target tracks are located in earth coordinates, immediately suitable for display on maps and in third-party systems. Display processing supports numerous rich real-time displays including scan-converted video, clutter-suppressed video, target echo-trails video, map underlay, detection and detection history overlays, track and track history overlays, etc.

The term *target data* as used herein refers to both the target tracks and the detections, including the particular linkages between the detections and each track. Tracks are composed of a series of track updates that occur every scan. Each update includes a time stamp, target ID, radar ID, position (latitude, longitude or UTM), speed, heading, intensity, height, track covariance, etc., characterizing the complete behaviour of the respective target. The target data also includes various metadata indicative of the processing parameters so that the configuration of the radar system is completely characterized. This is essential for investigative, research, and validation purposes, in order to insure target data integrity. It is this target data that is stored locally, 24/7, as well as being streamed over the network in real-time to the RDS.

An integrated graphical user interface (GUI) is available to configure and control all functions of the DRP. The GUI is also accessible over the network, so that the radar technician responsible for maintaining the radar system need not physically be located at the radar(s). This remote desktop capability is also a convenient way to provide the DRP's video display to remote users on the network. However, this remote video viewing is not to be confused with the real-time target data streaming that sends digital target information (i.e. track data) to the RDS so that it can be accessed and automatically processed by other applications.

The DRP also provides interfaces to external applications so that it can, for example, be queried for subsystem health and controlled for automated radar scheduling (ARS) purposes. Automated scheduling is important in situations where either one may wish to employ a particular sampling regime, or the radar resource is shared for different missions, or blackout periods must be enforced.

For affordability and flexibility, the TCP/IP-based network can be any suitable (T1 speeds or better) wired or wireless LAN, WAN or public network such as the Internet.

Each radar on the network streams its target data to the RDS which serves several important functions:

- it acts as a central repository for the target data
- it organizes the target data from multiple radars to support SQL access and Web services (open architecture)
- it provides specialized real-time access of the target data to the Radar Fusion Engine (RFE)
- it provides specialized real-time access to remote analyst workstations (TrackViewer Workstations "TVWs")
- it provides specialized real-time access to third-party systems
- it provides specialized real-time access to the SARD Processor
- it provides specialized real-time access to the TC Processor
- it supports multi-sensor integration applications (e.g. cueing cameras, bird deterrent devices, etc.)

The RFE accesses radar target data via the RDS from a number of radar sensors. It updates a master track list in the RDS in real-time to produce fused tracks in support of a common operating picture (COP). The TC Processor works in a similar manner. Rather than updating a master track list, however, it updates track classification attributes based on classifier models that use the multi-dimensional tracks as input.

Multiple remote analysts (users) can access the target data from any radar or the COP in real-time and process that data for their own purposes using their own TVW. For example, one wildlife biologist might configure his TVW to send automated perimeter alerts to his Blackberry so that he knows when birds are moving into the aerodrome. Another wildlife staff member might simply wish to have a real-time target track display in her vehicle set to a range of interest as she goes about her duties on the airfield. A third user may wish to employ a TVW to rapidly replay all bird movements that occurred the preceding night while she is having her morning coffee. Yet another TVW might be located in the air-traffic control tower showing the real-time COP.

The SARD Processor interacts with the RDS and provides a Web-services interface to external users. For example, it can provide a statistical target data feed to a national airport bird-advisory system. Airlines could access this system for flight planning, for example. Rather than feeding individual bird tracks to such a system, the SARD Processor applies temporal and spatial integration to the target data. Then bird traffic density information (over a user-specified spatial grid and time-frame) can be instantly realized in a Web application, with updates occurring on the order of minutes.

The third-party interface can support virtually any application. The entire network and target data streaming architecture provides the flexibility to introduce new applications, including research-based ones, in a straightforward manner, to any authorized user. Given the history of other distributed national radar systems (e.g. ASRs, WSRs), it makes good sense today to build flexibility into any new radar deployments that could ultimately have a national and international footprint.

3. AVIAN RADAR DEVELOPMENTS PAST & PRESENT

Almost as soon as military radars were deployed during World War II, researchers observed that birds could be detected by them [Lack and Varley, 1945]. It is no wonder then, that by the early seventies when inexpensive marine radars were first widely available, researchers began using them for studying birds.

Since then, major developments have occurred in avian radar. The stages of development proceed from *concept* (and design) to *working prototypes* (R&D), to *production*. Working prototypes usually require manual methods and extensive training and expertise. Production versions usually try to automate several of the processes to improve reliability, make them more user-friendly, improve consistency and repeatability, and improve performance and efficiency.

Useful end-user applications tend to be available throughout the development cycle of new products. This is indeed the case for avian radars, where the end-user biologists and ornithologists were early adopters of the technology, even to the point where they had to put on the hat of a "radar engineer" in order to advance the developments, until radar companies recognized the market needs. Avian radar systems are available today that are already useful in various applications. Their usefulness will only increase as developments get closer to providing the full set of avian radar systems capabilities described in Section 2.

3.1 *Development Timeline*

The development timeline discussed herein is organized into three periods of avian radar development:

1. manual target extraction methods (before 2000)
2. automatic target extraction methods (after 2000)
3. multi-sensor integration and fusion (after 2005)

Figure 2 illustrates this timeline, which is discussed further in the remainder of this paper.

3.2 *Manual Target Extraction*

Prior to around 2000, avian radars were largely used and developed by researchers, the military, and environmental consulting firms for carrying out EIAs and for monitoring birds in the context of BASH management. This period can be characterized by the use of COTS marine RSTs, some specialized software, and largely manual methods for target extraction. Cameras and frame-grabbers were used to capture radar video screens. Grease pencils and spreadsheets were the tools of the day to indicate detected bird targets on the radar PPI (plan position indicator) display and to record their characteristics (e.g. position, heading, speed, quantity, etc.). Various firms and researchers developed and reported on their methods (e.g. [Mabee et al, 2006]). These manual methods are still in use today and have gained scientific acceptance.

Marine radar arrays, when mounted horizontally ("an H-array"), can provide good coverage and position estimates, but provide little to no height information; similarly, when mounted so that the array spins vertically ("a V-array"), it provides good height estimates, but can only see targets when they cross into the vertical plane that contains the vertically spinning antenna [Weber et al, 2005; Larkin 2005, Mabee et al, 2006]. An H-array and a V-array have very different coverage volumes with very limited overlap. As a result, one cannot use a pair of H and V arrays simultaneously to provide 3D bird and aircraft tracking throughout the desired radar coverage volume of an airport. Nevertheless, they can be used independently or in concert to statistically sample the volume. As a result, during this period of avian radar development, methods were developed for using the H-array and the V-array independently. The V-array works quite well at sampling a slice of the volume in order to estimate height distributions for birds.

3.3 *Automated Target Extraction*

With Geo-Marine Inc.'s (GMI) development in 2000 of the first automatic vertical scanning radar for bird detection, the automated target extraction period began. It had become clear to many that avian radars could detect birds well enough for several useful applications, and automation would be the key to future development.

Between 2000 and 2005, major advancements in automatic target extraction were introduced into the market, spurred in no small way by the interest of the U.S. Navy, Air Force and Marines Corps, the FAA, Transport Canada and others in improving aviation safety with respect to bird strikes. Both Sicom Systems Ltd. (a radar engineering company) and DeTect Inc. entered the market. Enhancements from GMI (under the MARS brand), and new products from DeTect Inc. (under the name of Merlin™) and Sicom Systems Ltd. (under the brand Accipiter®) were introduced.

DeTect developed stand-alone, trailer-mounted, production versions of radars using H-arrays, V-arrays and combined H-array / V-arrays, with automated target detection methods. The RSTs employed are COTS marine radars.

Sicom developed turnkey, stand-alone, production versions under the Accipiter® brand, motivated by the distributed multi-radar system architecture illustrated in Figure 1. As a result, platforms and users were abstracted in the design, resulting in a family of Accipiter® radar components that can be easily integrated together to serve either as stand-alone configurations on virtually any platform, or for wide-area networks (see Section 3.4). The heart of this product family is the Accipiter® DRP which has most of the functionality contained in the DRP shown in Figure 1 and described in Section 2.2. The Accipiter® DRP includes the first (and only) real-time, PC-based implementation of the MHT/IMM tracking method, the military gold standard for tracking small maneuvering targets such as birds [Weber et al, 2004; Bhattacharya et al, 1998; Blackman S, 2004; Nohara et al, 2005P]. With MHT/IMM, automated target extraction now includes sophisticated, real-time tracking of large numbers of individual birds and flocks.

The Accipiter®-AR (avian radar) DRP was introduced in 2004 and integrated with the U.S. Navy's BirdRad system as an upgrade to automate its target extraction methods. The upgraded system is now referred to by the Navy as eBirdRad [Weber et al, 2005; Brand 2004].

The BirdRad and eBirdRad systems incorporate an army-surplus dish antenna selected and integrated by Dr. Sidney Gauthreaux of Clemson University. This dish antenna (see [Weber et al, 2005]) has a relatively narrow (4 degree) pencil beam that would usually be inclined in elevation several degrees to follow the typical arrival or take-off glide slope of an aircraft. The parabolic dish would scan horizontally like an H-array, but its vertical beamwidth (being 4 degrees rather than say 20 degrees) was fine enough that height estimates could be computed for any targets in the beam. For night-time migration, the dish can be elevated higher to better sample birds overhead.

The advances during this period have moved avian radar systems much closer to the design needed for BASH management shown in Figure 1. DRPs have been developed that incorporate state-of-the-art, real-time, automatic target extraction methods. With the integration of parabolic dish antennas, for the first time, real-time, 3D target information can be acquired for all bird and aircraft targets in the 360 deg field of coverage of the radar. In other words, the 3D target trajectories (lat, long, and height) versus time became available.

3.4 *Multi-Sensor Integration and Fusion*

The major system enhancements for the period from 2005 to present can be organized into the following areas:

- radar data management and distribution
- multi-radar fusion
- multi-sensor integration
- sensor improvements

In the area of radar data management and distribution, the Accipiter® RDS, the Accipiter® RRC, and the Accipiter® TVW were introduced. These products are available as COTS items, and have all of the functionality of the RDS, RRC and multiple remote analyst workstations (clients), respectively, as described in Section 2.2. Furthermore, an Accipiter® Automated Radar Scheduler (ARS) has been introduced, along with automated health monitoring.

Under FAA and DHS (Department of Homeland Security) evaluation programs, Accipiter® radar networks have been deployed and operated with two or more radar nodes, containing RST, DRP, RRC, RDS, TVW, third party and COP elements in Figure 1. The affordability, reliability, and performance capabilities of the networked avian radar wide-area surveillance system architecture (Figure 1) have been demonstrated. Reliability and high performance have been achieved even under conditions of intense target movements that generated hundreds of real target tracks from each node continuously for extensive time periods. The radar systems were maintained and supported out of country, and remote users from two countries shared real-time target data and generated local, and user-specific displays.

An Accipiter® avian radar fusion engine (RFE) has been under development for several years now, and a beta version (working prototype) is expected to be released by the end of this year. Target synchronization and registration from multiple radars with overlapping coverage have already been demonstrated.

There have also been advances reported in the areas of sensor integration. Some companies have reported on R&D integration with acoustic sensors; and the aforementioned DHS program deployed radars integrated with cameras (color and thermal) and automatic identification system (AIS) sensors. These efforts are directed toward automatic target classification which is currently in the R&D stage.

Finally, there have been sensor improvements introduced into the market under the Accipiter® brand. A production parabolic dish antenna with finely-adjustable inclination angle has been introduced and integrated with COTS marine radars. This RST configuration serves as the front-end of Accipiter® radars requiring pencil beams for surveillance. In addition, to further improve vertical coverage and height estimation accuracy, a dual-dish Accipiter® avian radar system configuration has been developed. This configuration was recently selected and deployed at Seattle-Tacoma International airport for evaluation under the aforementioned FAA program [Herricks 2006]. This configuration brings the market one step closer to fully realizing the kind of 3D tracking radar coverage envisioned by the BASH radar design of Figure 1.

4. AVIAN RADAR DEVELOPMENTS IN THE FUTURE

Additional enhancements can be expected over the next several years to further improve avian radar systems, and to fully realize the system design shown in Figure 1, for BASH management and other applications.

4.1 *Automated Target Extraction Improvements*

Current RSTs and DRPs do not accurately estimate the size (radar cross-section, or RCS) of tracked targets. This capability requires calibration of the amplitude response of the radar transceiver, which is under development. Once this capability is achieved, having real-time target RCS estimates will be an important first step in the classification (identification) of targets.

Identifying what radar target tracks really are is one of the great remaining challenges in avian radar system design. Target classification rules could be created to use all of the available information from each track (e.g. velocity, height, RCS, history, etc.). The development of such rules and their implementation in a TC processor require much further experimentation and research. The goal for classification need not be precise species identification (e.g. crow versus falcon), but instead a more general danger assessment (e.g. flock of large fast birds).

4.2 *Multi-Sensor Integration and Fusion*

The integration of radar target data with other data sources is an important part of avian radars requiring further development. Data sources include other real-time sensors (cameras, acoustics, etc.) as well as historical and empirical information that will be useful for further characterizing bird targets, and for improving the development of TC processors. A related future development is to use radar bird target data information to automatically cue deterrents.

Further development of the RFE is ongoing with new products expected in the near future. An avian RFE will provide a unified COP for a large airport deploying multiple avian radar nodes.

Integration of widely dispersed avian radars can provide regional, national or continental bird strike advisory networks. A recently awarded DoD program [ESTCP 2007] will carry out studies that will investigate certain aspects of the integration of avian radars deployed on a continental scale. Information from programs like this, and from the aforementioned evaluation programs will result in numerous third-party applications being developed to exploit these avian radar networks.

4.3 *Sensor Improvements*

The dual-dish configuration discussed in Section 3.4 can be further improved through additional integration. These improvements will result in even better height estimation versus coverage trade-offs, and reduced costs and increased reliability through hardware integration. Instead of two RSTs, an integrated, RST is the subject of a new R&D program that will continue over the next few years to produce a dual-beam RST under the Accipiter® brand.

4.4 *Validation and Certification*

Sophisticated avian radar systems are now available. These need to be validated under different conditions with ground-truthed targets using scientific methods; and the validation methods and results need to be reported in the open literature and subject to peer review in order to gain acceptance. Two such efforts have recently begun [ESTCP 2007 and Herricks 2006] and initial results can be expected to be reported in the near future.

5. SUMMARY AND CONCLUSIONS

Table 1 below summarizes requirements, present capabilities, and future developments. This table emphasizes the point that useful avian radars are available today, and that performance will only improve in the future. Systems that adhere to a well-defined network architecture such as in Figure 1 will be able to protect customers' existing radar investments, through evolutional upgrades.

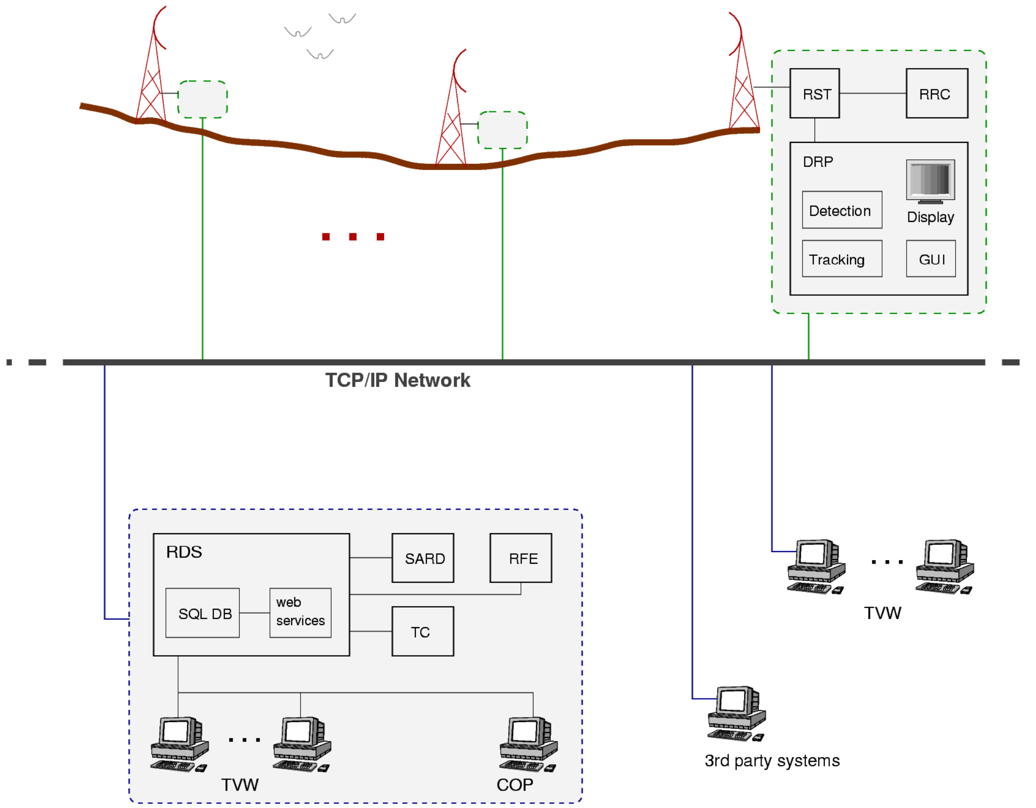

Figure 1: Desired 3D Avian Radar Systems Design

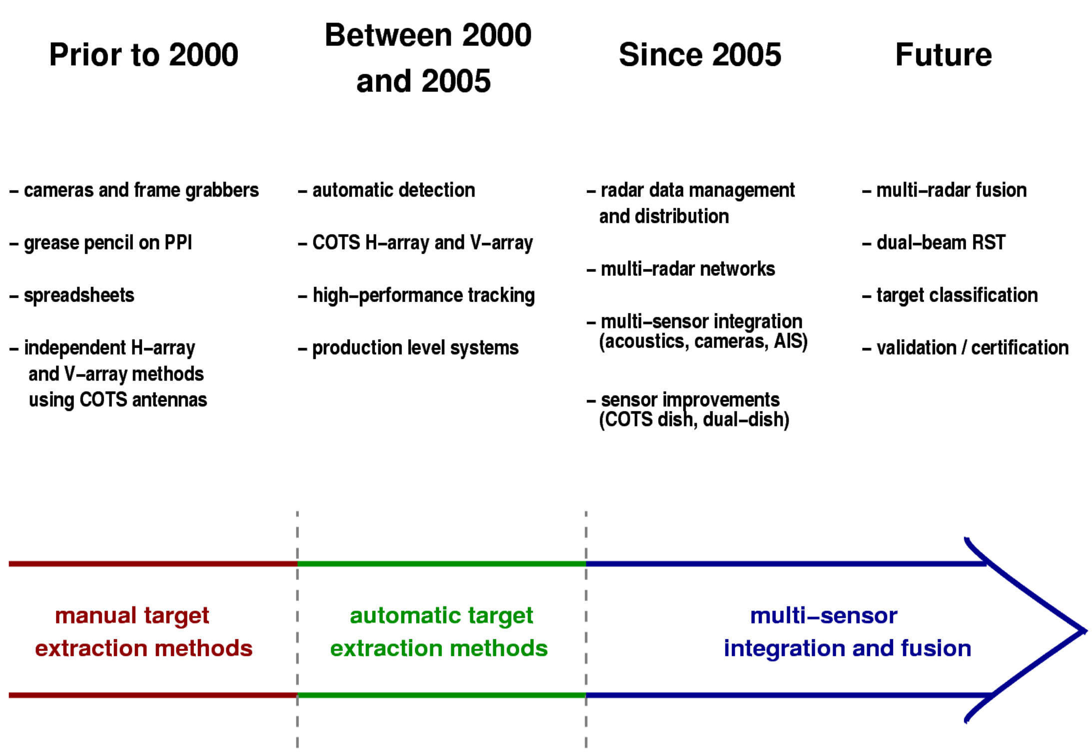

Figure 2: 3D Avian Radar Development Timeline

Table 1: Avian radar capabilities present and future

Requirement for BASH Management at Airports	***Current Status Looking at entire Market as a whole***	***Future Developments***
Real-time 3D bird and aircraft tracking	2D fully operational 3D using dish (limited volume)	3D using dual-beam RST Full volume & good height
Real-time GIS	Fully integrated and operational	
Remote operator displays	Fully customizable and offering a wide range of display layers	
Real-time alerts	Fully integrated and operational	More applications
24/7 target data storage	Fully integrated and operational	
Real-time streaming of target data	Fully integrated and operational	
Multiple remote analyst workstations	Fully supported	
Rapid replay of target data	Fully integrated and operational	
Automated radar system scheduler	Fully integrated and operational	More applications
Target data interfaces to third party apps	Fully working for a few applications	More applications
Multiple radar fusion	In advanced development	Beta version end of 2007
Real-time TC Processor	In R&D stages	Needs significant development
SARD Processor	Working prototypes	Production models by 2008
Multi-sensor integration	In R&D stages	Needs significant development
EMC with other airport RF systems	X-band marine RSTs tested OK	Other bands need testing
Affordable/maintainable	Many configurations proven, production	Integrated Logistics Support TBD

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