IMPLEMENTATION OF A LOW-COST SSR/ADS-B AIRCRAFT RECEIVER DECODER (SY-100)

Bennett Cohen, Rannoch Corporation, Alexandria, Virginia

Alex Smith, Rannoch Corporation, Alexandria, Virginia

Abstract

For many aviation research and development programs it is necessary to acquire accurate aircraft position and identification information. Many previous analyses in terminal areas have used radar surveillance data recorded from terminal radar systems. These analyses have required conversion and post processing of radar tapes from air traffic control. Problems with this type of analysis include a low data update rate (once per 4.8 seconds in the terminal area), sufficient coverage at low levels (below the radar cut-off), data latency (it can be up to 2 seconds old), and the intensive task of manually sorting and parsing data from the tapes. To assist with several research and development programs Rannoch has developed and implemented a real time stand alone radar receiver decoder system. The system decodes all radar data on the 1090 MHz and 1030 MHz (downlink and uplink) including Mode S, TCAS, ATCRBS, ADS-B, and IFF. In a typical terminal area the system decodes real time aircraft radar data at up to 10 Hz from each aircraft. This paper describes the application of the system to assist with several Air Traffic Control (ATC) research programs including wake vortex research. The equipment set up and integration with a wake vortex sensor suite is described and results are presented from field trials at JFK International Airport. This paper contains only the understanding and views of the authors and is not intended to reflect the official position or view of the US Government, the FAA or NASA.

Introduction

The Volpe Center, NASA and the FAA have been conducting wake vortex research at JFK, Memphis, DFW and other airports for a number of years. The purpose of their research is to characterize the behavior of wake vortices and to ultimately be able to predict their movement so that ATC will be able to warn aircraft before a wake vortex encounter. A key element in detecting and characterizing wake vortex behavior is determining what type of aircraft generated a particular set of vortices. In the past this data was either collected by an observer, (who had to be very familiar with different aircraft types), or by obtaining FAA radar data and determining which aircraft were the aircraft of interest and matching them up with the data from the wake vortex sensors. These methods proved to have numerous drawbacks. An observer was costly to employ around the clock, and occasionally made mistakes in identification and time recording. At the end of data collection, all of the observer’s data had to be integrated by hand with the data from the wake vortex sensors.

Aircraft data from ATC radar required that prior arrangements be made with the FAA. Afterwards, this radar data required considerable effort to separate out the aircraft of interest from the rest of the aircraft and to match the radar data with the corresponding sensor data. Because airport surveillance radar rotates once every 4.8 seconds, the aircraft tracks are sometimes difficult to follow. As aircraft get close to the radar antenna they occasionally go below the coverage of the antenna, making it difficult to track the aircraft close in to the airport. Because of these shortcomings, Rannoch Corporation, under contract from the Volpe Center, integrated an SSR decoder to automatically identify landing aircraft models and types as well as provide other information.

Why Mode S

Rannoch set out to build aircraft identification equipment that would be low cost, passive, stand alone, and automated. We wanted to build equipment that would cost a fraction of a TCAS unit, that didn't interfere with any ATC or other equipment, and that would operate continuously in an unattended environment. Additionally, the equipment had to comply with the guidelines established in the ICAO Mode S SARPS, the RTCA Mode S MOPS and the Draft FAA / Industry ADS-B requirements. With these requirements we decided that the best approach would be to develop a device that listened to the Mode S transponder transmissions from aircraft. Mode S transponders are required equipment on all passenger carrying aircraft with more than 30 seats. This requirement includes foreign carriers that operate into the U.S. Many aircraft with 10 to 30 seats are also equipped with Mode S transponders, although this is not a requirement. Many business jets carry Mode S transponders as well.

Evolution of SSR

In the early days of radar, targets were identified by directing megawatts of RF energy through a narrow rotating beam of directed energy. This RF energy would be reflected off the target and some of the energy would bounce back to the transmitting radar antenna. A drawback of this method, called primary radar, is that the return RF energy from the target diminished as an inverse function of the square of the distance to the target. For example, the returned energy from a target that is twice as far away than another target is only one quarter of that of the closer target. Then in the 1950's a method was developed that extended the useful range of radar by eliminating the problem of the inverse square law. Aircraft began carrying transponders, radio transmitters that replied to the radar interrogation with their own RF energy as opposed to reflected radio energy. This is called secondary surveillance radar (SSR). The earliest methods of SSR enabled a target aircraft to reply to the interrogating radar with one of 64 (2^6) possible pulse codes. Further refinement of the technique enabled target aircraft to reply with up to 4096 (2^{12}) possible unique pulse codes used for discrete identification. This was called Mode A. Mode C enabled the ground based interrogator to ask for the pressure altitude of the aircraft from an encoding altimeter.

In the 1980's the Mode S transponder format was established. It allows for the transmission of many more pulses and therefore, much more information. The Mode S format actually consists of a subset of 25 possible uplink and downlink formats. The "short" downlink formats contain 56 pulsed bits of information, while the "long" formats contain 112 pulsed bits. Figure 1 attempts to show the relative length of the Mode A, C, and S short and long reply formats. Note that the Mode S long format has been truncated due to printing size considerations. The Mode S long formats are actually 120 microseconds long.

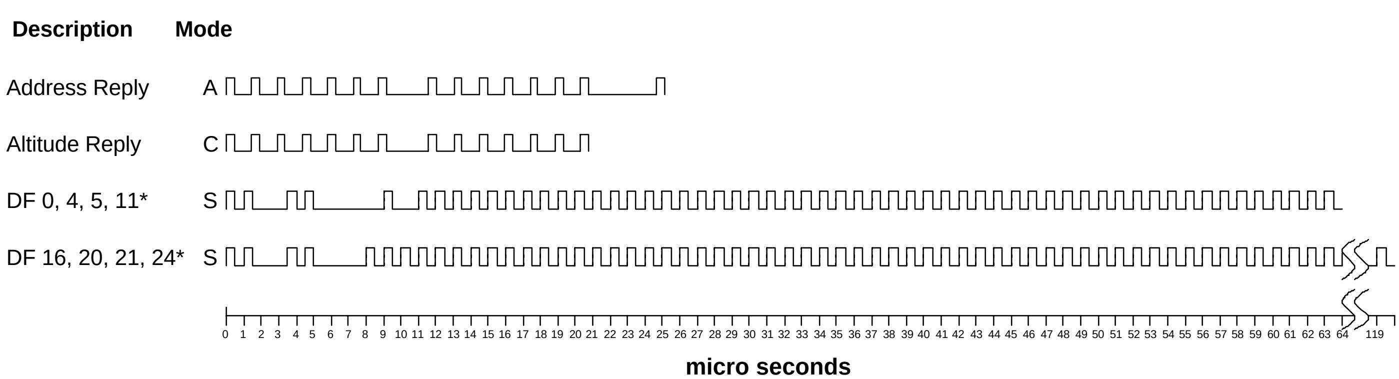

Figure 1. 1090 MHz Formats

At present only formats 0,4,5,11,16,20, 21 and 24 are used in aviation. The Rannoch decoder is capable of decoding all 25 formats. One format, DF 17, will be the first format used for the much touted ADS-B (Automatic Dependent Surveillance-Broadcast) system. The format will contain information on aircraft latitude, longitude and altitude. This position data can be from GPS or other navigation systems. Aircraft will transmit DF-17s once per second without being interrogated. This is referred to as a "squitter" and will enable both aircraft and ground based controllers to receive very accurate position information. The Rannoch decoder was used during surface operation trials of the ADS-B system in July, 1997 at Atlanta Hartsfield International Airport.

How it Works

The Rannoch decoder is comprised of an antenna, a 1090 MHz receiver, an analog to digital converter and decoder, and Pentium processor and software as shown in Figure 2.

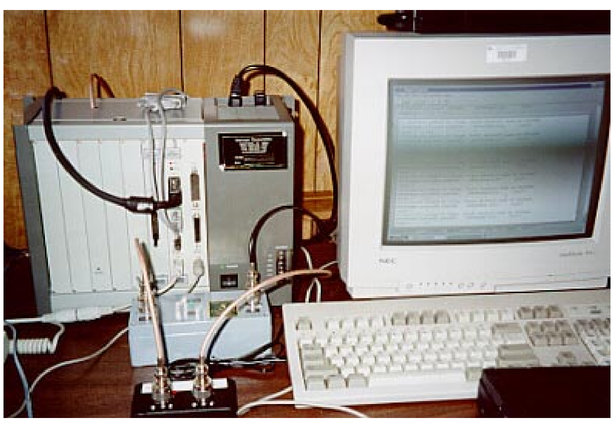

Figure 2. Decoder, Receiver & Processor

The antenna used for the wake vortex research project at JFK was a 4 pole yagi directional antenna (see Figure 3). The directional antenna allows for adjusting the reception of the decoder to the area of interest, which in this case is the final approach course. It also eliminates reception from other aircraft on the surface or operating to a parallel runway. A variety of different antennas including directional, omni-directional and sector antennas can be used with the decoder to achieve various coverage patterns.

Figure 3. Yagi Directional Antenna Used To Monitor Approaches to One Runway

The 1090 MHz receiver is a small (less than 2 lb.) unit that can either be attached to the antenna for maximum effectiveness or can reside next to the decoder processor. It is also capable of receiving 1030 MHz for monitoring ground and TCAS interrogations. The receiver receives DC power through the coax cable and can be switched remotely to operate at either 1030 MHz or 1090 MHz. The receiver was designed to operate with the modulation and bandwidth of the uplink and downlink formats. Our first prototype (shown in Figure 4) achieved a sensitivity of -90 dBm.

Figure 4. Mast Mountable SSR Receiver To Maximize Range

The analog to digital converter and decoder have been designed into a range of hardware architectures, from the PC ISA bus on the low end to the VME bus for commercial applications. The decoder circuitry is re-configurable at any time. The software extracts the encoded Mode S address, converts the address to a U.S. registration number (N number) and does error detection and correction. It also extracts the altitude, which is pressure altitude reported in either 25' or 100' resolution. Then, the N number is looked up into the database of all registered US aircraft. The output of the decoder consists of a computer time stamp, Mode S address, downlink format, N number, owner/operator, make, model, serial number and altitude (see Figure 5). The software is easily modifiable to include or exclude any fields from the database. The data is sent to a monitor, the hard drive and a serial port in real time. The software also enables a signal strength threshold to be set which excludes the reception of transponder transmissions which fall below a specified level.

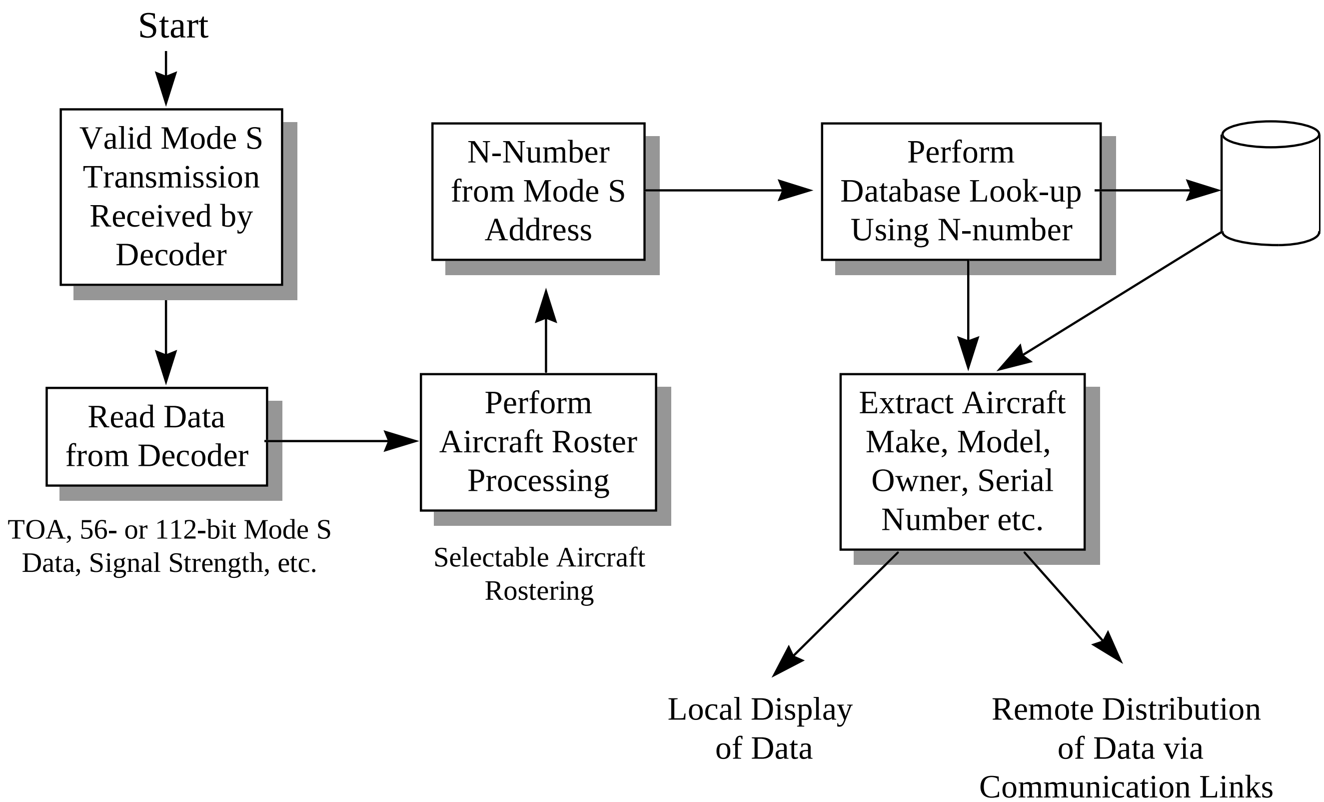

Figure 5. Real Time Decode & Look Up Process

Deployment Considerations

The purpose of the decoder at the JFK wake vortex sensor site was to identify individual aircraft as they passed over the wake vortex sensors. These sensors are located just inside the middle marker for runway 31R, about 3800 feet from the touchdown zone. A directional yagi antenna was used to focus on aircraft on final approach to 31R and ignore those on the ground and on parallel approach to runway 31L. The signal strength threshold was set to a level where signals were received for about three to thirteen seconds for each aircraft as it approached the sensor area. The variation in reception duration time is due to a number of factors including differences in transponder output power, antenna gain and ground speed. The signal strength threshold was set to a level that did not exclude any aircraft. On this model thresholds were selectable, via graphical user interface, from -90 dBm to -20 dBm.

Decoder Output

The following excerpt from the decoder output file shows typical data for an aircraft as it approaches the wake vortex sensor area. The first field of data is a time stamp from the computer's internal clock. The time is displayed in hours:minutes:seconds:hundredths. The next field is the Mode S address expressed as a six digit hexadecimal number. The third field is the downlink format. Notice in the following example that DF 0's are most prevalent. They are responses to TCAS interrogations. DF 4s, 11, and 20s also appear in this example. The next field is the U.S. registration number, or "N" number, which is derived from the Mode S address. The N number is used to look up into a database of US registered aircraft. The next five fields, owner/operator, manufacturer, model, serial number, and weight class all come from the database. The last field is pressure altitude which is encoded in downlink formats 0, 4, 16 and 20.

In the following typical data sample (Figure 6) from a United Airlines Boeing 777, twenty-five transponder transmissions were decoded over a period of about ten seconds. During that time the aircraft's pressure altitude decreased from 250 feet to 150 feet.

```
09:45:45:66 AAB001 11 788UA  UNITED AIR LINES INC  BOEING  777-222  26942  CLASS 3
09:45:46:87 AAB001 00 788UA  UNITED AIR LINES INC  BOEING  777-222  26942  CLASS 3   250
09:45:47:04 AAB001 00 788UA  UNITED AIR LINES INC  BOEING  777-222  26942  CLASS 3   225
09:45:47:70 AAB001 11 788UA  UNITED AIR LINES INC  BOEING  777-222  26942  CLASS 3
09:45:48:08 AAB001 00 788UA  UNITED AIR LINES INC  BOEING  777-222  26942  CLASS 3   225
09:45:48:30 AAB001 00 788UA  UNITED AIR LINES INC  BOEING  777-222  26942  CLASS 3   225
09:45:48:52 AAB001 00 788UA  UNITED AIR LINES INC  BOEING  777-222  26942  CLASS 3   225
09:45:49:07 AAB001 00 788UA  UNITED AIR LINES INC  BOEING  777-222  26942  CLASS 3   200
09:45:49:29 AAB001 00 788UA  UNITED AIR LINES INC  BOEING  777-222  26942  CLASS 3   200
09:45:49:45 AAB001 11 788UA  UNITED AIR LINES INC  BOEING  777-222  26942  CLASS 3
09:45:49:62 AAB001 04 788UA  UNITED AIR LINES INC  BOEING  777-222  26942  CLASS 3   200
09:45:50:06 AAB001 00 788UA  UNITED AIR LINES INC  BOEING  777-222  26942  CLASS 3   200
09:45:50:28 AAB001 00 788UA  UNITED AIR LINES INC  BOEING  777-222  26942  CLASS 3   200
09:45:50:50 AAB001 11 788UA  UNITED AIR LINES INC  BOEING  777-222  26942  CLASS 3
09:45:50:94 AAB001 00 788UA  UNITED AIR LINES INC  BOEING  777-222  26942  CLASS 3   175
09:45:51:10 AAB001 00 788UA  UNITED AIR LINES INC  BOEING  777-222  26942  CLASS 3   175
09:45:51:43 AAB001 20 788UA  UNITED AIR LINES INC  BOEING  777-222  26942  CLASS 3   175
09:45:51:60 AAB001 20 788UA  UNITED AIR LINES INC  BOEING  777-222  26942  CLASS 3   175
09:45:52:09 AAB001 00 788UA  UNITED AIR LINES INC  BOEING  777-222  26942  CLASS 3   175
09:45:52:31 AAB001 00 788UA  UNITED AIR LINES INC  BOEING  777-222  26942  CLASS 3   175
09:45:52:53 AAB001 00 788UA  UNITED AIR LINES INC  BOEING  777-222  26942  CLASS 3   175
09:45:54:07 AAB001 04 788UA  UNITED AIR LINES INC  BOEING  777-222  26942  CLASS 3   150
09:45:54:23 AAB001 04 788UA  UNITED AIR LINES INC  BOEING  777-222  26942  CLASS 3   150
09:45:55:06 AAB001 00 788UA  UNITED AIR LINES INC  BOEING  777-222  26942  CLASS 3   150
09:45:55:28 AAB001 00 788UA  UNITED AIR LINES INC  BOEING  777-222  26942  CLASS 3   150
```

Figure 6. Sample Decoder Data Real Time Output

Data Interpretation and Analysis

Descent Profiles

Descent profiles can be generated easily from the decoder data. Figure 7 shows the descent profiles for a SAAB 340 and an A320 Airbus. The SAAB was two minutes in trail of the Airbus on a visual approach to JFK's 31R. The graph clearly shows that the SAAB was above the flight path of the preceding Airbus. Perhaps the pilot of the SAAB was trying to stay above the wake vortices of the Airbus, or perhaps he was just making a longer landing to avoid a lengthy taxi to his gate.

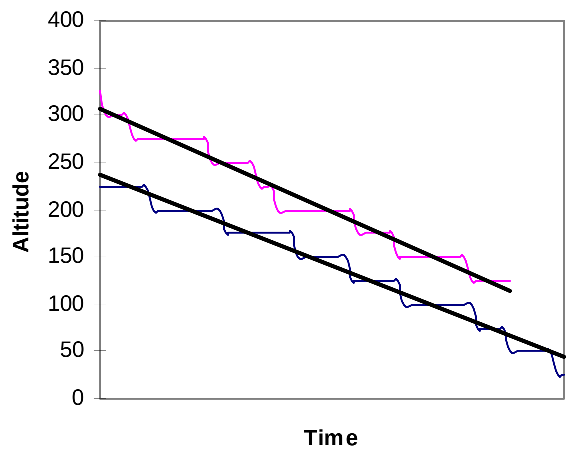

Figure 7. Aircraft Descent Profile Monitoring

Aircraft Type Breakdown

The decoder data can also be used to generate a breakdown of the type of aircraft that landed on a particular runway. The following pie chart (Figure 8) shows a breakdown of the aircraft types that landed on JFK's 31R in a 24 hour period. It is interesting to note that over 40% of the aircraft were twin turboprop commuters. Analyzing data over a longer period of time would provide statistics on aircraft separation in IFR/VFR, and could be used to build a database of pairwise separations (i.e., achieved separation between each aircraft type and weight class).

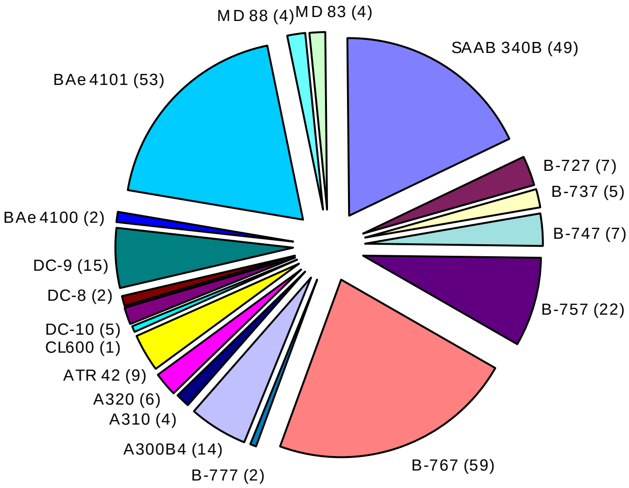

Figure 8. Aircraft Types Arriving at JFK

Ascent Profiles

The following graph of a DC-9 ascent profile (Figure 9) was generated from data collected at Rannoch's headquarters in Alexandria, Virginia. Aircraft arriving and departing Washington National Airport (DCA) are an excellent source of transponder transmissions in a terminal environment. The graph shows the DC-9 ascending at 2000 feet per minute.

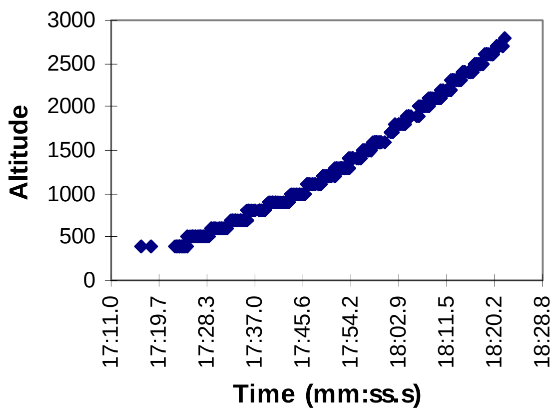

Figure 9. DC-9 Departure

Downlink Formats

The decoder receives and decodes all Mode S downlink formats, as well as Mode A, Mode C, and IFF. Each Mode S downlink format has a particular purpose. DF 0's are responses to TCAS interrogations. DF 4's are responses to ground based interrogations. DF 11's are "squittered" by Mode S transponders at a nominal rate of 1 Hz. Figure 10 shows the cumulative number of transmissions of DF 0's, 4's, and 11's for the DC-9 shown in the previous graph. Note that the DF 0's are transmitted much more frequently than the DF 4's or 11's. This is the expected response in a busy terminal area where there are many TCAS interrogations. Also note that the DF 11's are transmitted at the rate of about once per second. For this particular aircraft there are approximately 10 times as many TCAS replies as there are squitters or replies to ground interrogations.

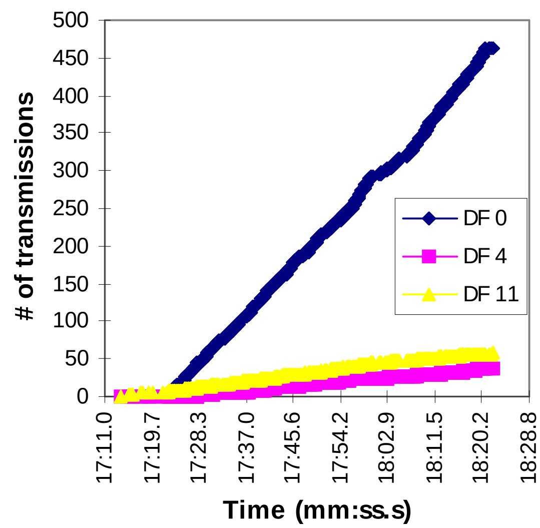

Figure 10. Cumulative DF0s, 11s, and 4s.

DF 4's, Response to Ground Interrogations

Figure 11 shows a more detailed view of the accumulation of DF-4 transmissions. A pattern of DF 4 replies can be seen every 4.8 seconds, which is the rotation rate of airport surveillance radar. Somewhat less obvious is a second pattern of replies, 180 degrees out of phase with the first pattern and also approximately every 4.8 seconds. Perhaps these two patterns of replies can be attributed to multiple interrogations during the testing of DCA's new ASR-9 prior to the decommissioning of the old ASR-7.

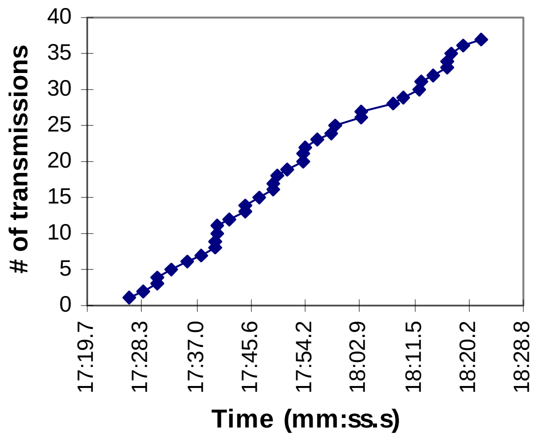

Figure 11. Response to Ground Interrogations

DF 16's, TCAS Resolution Advisory

Downlink format 16's are transmissions which are used by Traffic Alert and Collision Avoidance System (TCAS) units to communicate between aircraft. Figure 12 clearly depicts the beginning and end of a TCAS Resolution Advisory (RA) transmitted by a B-737 aircraft approaching Washington National Airport. TCAS RAs are instructions to the pilot to either descend or climb based on a TCAS encounter. We cannot tell, from the limited data in this instance, if the RA was a false alarm or not.

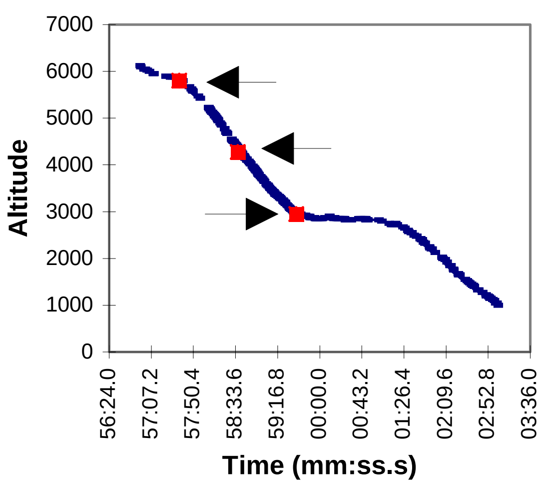

Figure 12. Aircraft Descending with DF 16s

Limitations

The ability of the decoder to accurately identify an aircraft is dependent upon the accuracy of the database. As new aircraft are put into service, and as aircraft registrations occasionally change, the database becomes less reliable. Fortunately, most airliners do not change ownership that often and therefore their registration numbers are not likely to change. The database is updated and made available on a quarterly basis. The decoder is unable to determine the registration number of foreign aircraft because there is no direct correlation between a non-U.S. registered aircraft's Mode S address and its registration number. However, some countries have made databases of their registered aircraft and corresponding Mode S addresses available. Additionally, the decoder can be used at an airport to determine a particular foreign aircraft's Mode S address and this can be associated in the database with the aircraft's registration number which can be entered manually.

Results of Deployment

For the wake vortex project the decoder operated continuously from May 13 to May 27, 1998. During one twenty-five hour period on May 21-22, the decoder logged approximately 2 Megabytes worth of data. The size of the file on any given day depends primarily on how much runway 31R was used for arrivals. On days when the wind did not favor 31R there is no data because there were no aircraft that flew over the sensors. Virtually all of the decodes yielded useful data in terms of a time when the aircraft crossed the wake vortex sensor area.

Applications of the Technology

One possible application for the decoder is for the monitoring of aircraft which exceed noise restrictions. Many airports have restrictions on the level of noise that can be generated on takeoff or landing. Large airports typically have very sophisticated noise monitoring systems which tap directly into the airport surveillance radar to record flight paths. Smaller airports however, can not afford to spend as much money on this sophisticated equipment and their needs could be met with a much less expensive system that could correlate a noise event with a particular arrival or departure.

Another application for the decoder is landing fee collection. Landing fees generate millions of dollars of revenue for airport operators. Fees that are not collected are lost revenue. Currently airport operators use methods such as reviewing fuel receipts to determine the number of arrivals and type of aircraft that a given airline operated into an airport in a given month. The decoder could easily provide a list of aircraft operations sorted by airline on a monthly basis to an airport operator.

As a component of an ADS-B ground station, the decoder will be able to decode advanced downlink formats, such as DF-17, so that an Air Traffic Control display can be generated. Finally, as a component of a multilateration system, several decoders can be used to calculate time of arrival of transponder transmissions, then share this data with a central processor which will use triangulation to determine the precise location and track of an aircraft.

Conclusions

One of the main goals during the development of the decoder was to make it less expensive than other equipment that is based on the same technology, such as TCAS. As the system was custom designed, we were able to achieve our cost goals for production equipment. Other comparable systems are usually based on modified commercial equipment, such as TCAS, meaning that there is unused or inapplicable functionality which the user has to pay for. In terms of performance, the customized elements of the system determine the range and decode rate, offering an optimum solution. During our trials we demonstrated the ability of our system to decode Mode A, C, S, and IFF transmissions. The device has been operationally deployed in support of several air traffic control research programs at major airports across the U.S. Observed data rates are an order of magnitude higher than standard airport surveillance radar. The data is suitable for graphing ascent and descent profiles and detailed information is available on U.S. registered Mode S equipped aircraft. The receiver decoder technology can be used by airport operators for noise monitoring, and landing fee collection. Air Traffic applications include ADS-B ground stations and receivers for multilateration systems. This type of technology is a more practical way to conduct research at airports. Rather than requesting radar data tapes and parsing data manually data can be collected automatically and processed in real time.