Prototype ADS-B System in the Midwest: Description and Lessons Learned

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Abstract

The Federal Aviation Administrations (FAA), in coordination with United Parcel Service (UPS), is developing an air traffic management application called Airline-Based En-Route Sequencing and Spacing (ABESS). The mission of ABESS is to enable airlines to adjust the spacing of aircraft arriving at an en-route merge fix by up-linking speed advisories during the en-route flight phase.

ABESS — which resides on computers in the airline command center — requires frequently updated aircraft surveillance data which include position, velocity, altitude, and identification information. Since most UPS aircraft are equipped with Mode S Extender Squitter (ES) transponders, an effective and low-cost method for obtaining the required information is via Automatic Dependent Surveillance – Broadcast (ADS-B) ground stations that receive on 1090 MHz.

To enable ABESS development to proceed before the operational ADS-B system becomes available, the FAA's Surveillance and Broadcast Services (SBS) Program Office asked the Department of Transportation (DOT) Research and Innovative Technology Administration (RITA) John A. Volpe National Transportation Systems Center (Volpe Center) to install five Extended Squitter ADS-B ground stations in the Midwest. The FAA also asked that these stations be connected with a prototype data fusion and distribution network that is linked to the ABESS application. The stations provide ADS-B coverage between Kansas and Kentucky.

The Midwest ADS-B network ground stations receive and decode aircraft-generated Mode S ES messages utilizing Downlink Format 17 (DF-17). Each station assembles a continuous stream of All Purpose STructured Eurocontrol Radar Information EXchange. (ASTERIX) Category 33 (CAT-33) messages encapsulating the position, velocity, heading, call sign, and other pertinent information for aircraft within its receiving range.

ADS-B ground station information is fused with surveillance information from the FAA's extensive network of Secondary Surveillance Radars (SSRs) at the FAA William J. Hughes Technical Center (WJHTC) using a Multi-Sensor Tracker (MST). The results are sent to UPS's Global Operations Center at Louisville, Kentucky for ingestion into ABESS.

This paper describes the successful implementation of the Midwest Prototype ADS-B System, including its system engineering, data collection processes, and data conversion methods. The paper also addresses techniques for correlating ADS-B and radar surveillance data.

In addition to accelerating ABESS development, the Midwest Prototype ADS-B System has enabled the identification and formulation of approaches to the resolution of key issues for implementing an operational ADS-B network as part of the National Airspace System (NAS). These issues include: (a) accurately and reliably decoding the latitude/longitude data in Mode S DF-17 transponder messages; (b) constructing a CAT-33 output message when various data fields in the input DF-17 message are missing or corrupted; (c) detecting and accounting for differences in aircraft transponders; and (d) correlating messages from different surveillance sources.

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1. Background

The U.S.'s network of ground-based Secondary Surveillance Radars (SSRs) will, over the next several years, be augmented by Automatic Dependent Surveillance – Broadcast (ADS-B) utilizing aircraft position and other data derived from the Global Positioning System (GPS) [**1**]. Ultimately some SSRs that provide redundant coverage will be removed. The Federal Aviation Administration (FAA) Air Traffic Organization (ATO) created the Surveillance and Broadcast Services (SBS) program office to define and manage agency-wide resources in the development and implementation of ADS-B and Flight and Traffic Information Services – Broadcast (TIS-B/FIS-B) utilizing Ground Based Transceivers (GBTs) that also receive ADS-B messages

ADS-B is the backbone of the Next Generation Air Transportation System (NextGen) — the nation's vision for the National Airspace System (NAS) in the 2015-2025 time frame. ADS-B provides controllers with more accurate, frequent, and informative (e.g., intent) data than SSR. Moreover, ADS-B provides the same data to nearby aircraft, provided they are properly equipped. A less appreciated advantage of ADS-B is that all aircraft positions are reported in the same coordinate system, greatly simplifying the merging of reports received at different ground sites.

ADS-B will be deployed throughout the NAS using two downlink/uplink formats; Mode S Extended Squitter (ES) on 1090 MHz and Universal Access Transceiver (UAT) on 978 MHz. The prototype Midwest ADS-B network provides an opportunity to better understand issues and reduce the risks involved in implementing the Mode S ES link.

The Airline Based En-route Sequencing and Spacing (ABESS), as well as other air traffic management applications, will benefit from the improved accuracy and update rate of ADS-B. The first version of ABESS used surveillance data from the commercially available Aircraft Situation Display to Industry (ASDI). ASDI data originates at the Enhanced Traffic Flow Management System (ETMS), which supplies similar data to the FAA's Air Traffic Control System Command Center (ATCSCC) for traffic flow management.

Much of the information supplied by the ASDI — such as flight plan information and sector boundary crossings — was adequate for ABESS. However the rate at which aircraft position information was received (1 min interval) was not adequate.

To improve upon the ASDI update rate, a decision was made to use ADS-B data in conjunction with en route radar data obtained directly from the radar site. The nominal ADS-B update interval is 1 sec; the nominal en route radar update interval is 12 sec. An important second benefit of radar data is that it supplements the coverage of the Midwest Prototype ADS-B network.

Because ABESS requires a means for uniquely identifying each aircraft, a fusion process was devised to correlate radar-supplied 12-bit Mode A beacon codes with the 7-character flight IDs (typically the airline flight number or the aircraft tail number) available from ADS-B. A third data source, derived from the ETMS, is used in performing this correlation.

DF-17 messages originate from aircraft equipped with Mode S ES transponders conforming to either DO-260 [**2**] or the newer DO-260A [**3**] Minimum Operational Performance Standards (MOPS) published by RTCA, Inc. While the two MOPS versions are generally similar, an important area of difference is the way in which the quality of the navigation data is characterized. When a DF-17 message is received from a "new" aircraft (i.e., one not already being tracked), care must be exercised in deciding whether the transponder is DO-260 or DO-260A-compliant, as the processing is necessarily somewhat different (see Section 4 for details).

Another important difference is that DO-260A-compliant messages include Mode 3/A beacon codes, while DO-260 messages do not. Most automation systems — e.g., Automated Radar Terminal System (ARTS) and Host — use the beacon code to distinguish specific aircraft.

2. System Description

2.1 System Overview

Figure 3A block diagram of the Midwest Prototype ADS-B System is shown in Figure **1**. This system was deployed to support ABESS, whose purpose is to facilitate the merging of aircraft in the en route domain flying to Louisville International Airport – Standiford Field (SDF) from the western part of the U.S. The required ADS-B coverage region can be summarized as follows:

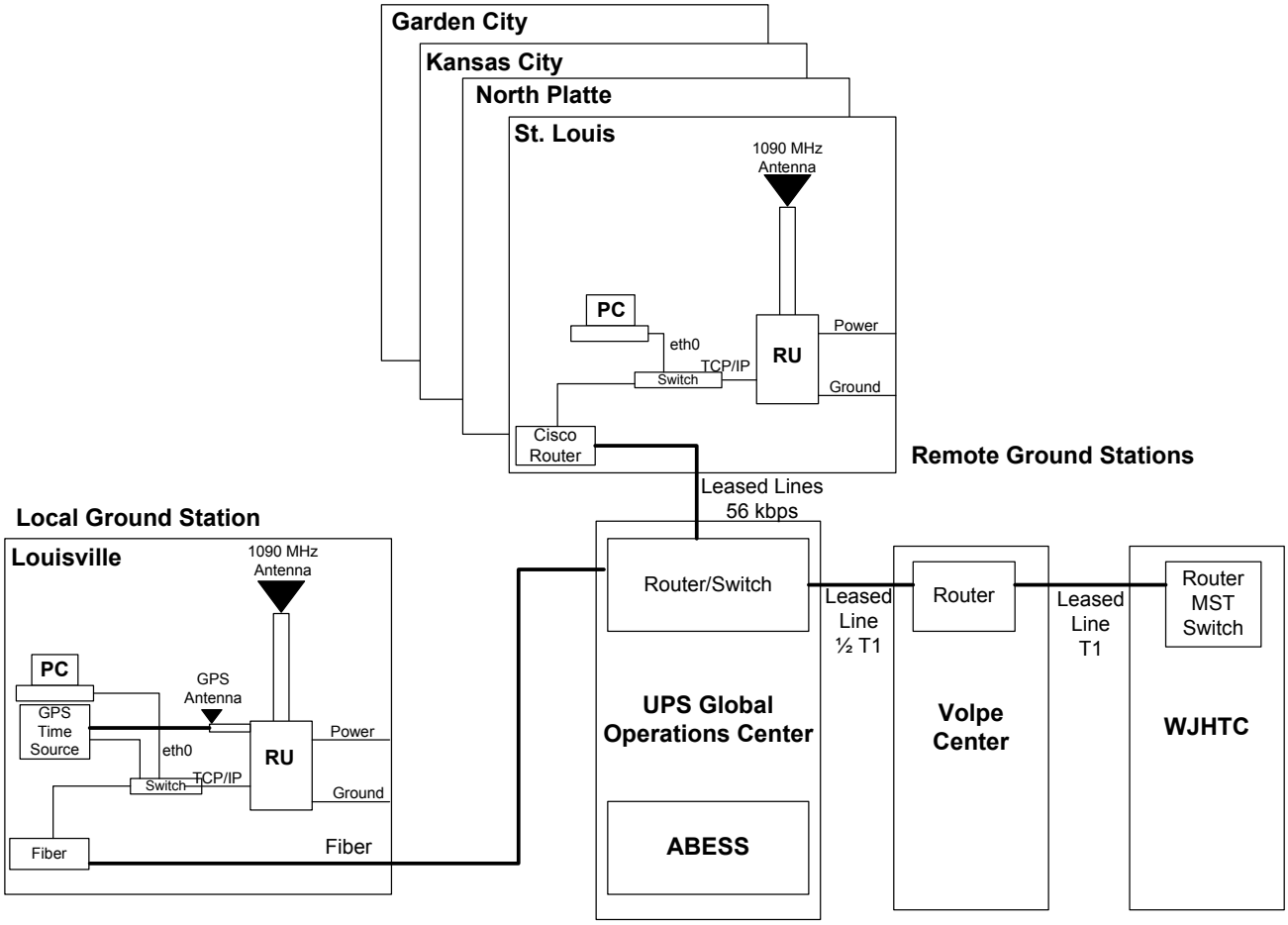

Figure 1: Midwest Prototype ADS-B System Diagram

- Within 90 min flying time to the west of SDF (equivalent to several hundred nautical miles)
- Five major air routes into SDF from the west, to a distance of roughly 1,000 nmi
- Above 20,000 ft Mean Sea Level (MSL)

To achieve this coverage, Mode S ES ADS-B ground stations were deployed at five locations:

1. Louisville, KY
2. Saint Louis, MO
3. Kansas City, MO
4. North Platte, NE
5. Garden City, KS

Figure 2 shows the predicted coverage for the ADS-B ground stations at 20,000 ft MSL, with range rings at 50 nmi intervals. Most importantly, this coverage allows aircraft to be sequenced into the Centralia, Kansas VORTAC (ENL) merging fix.

Each ground Station contains three primary components.

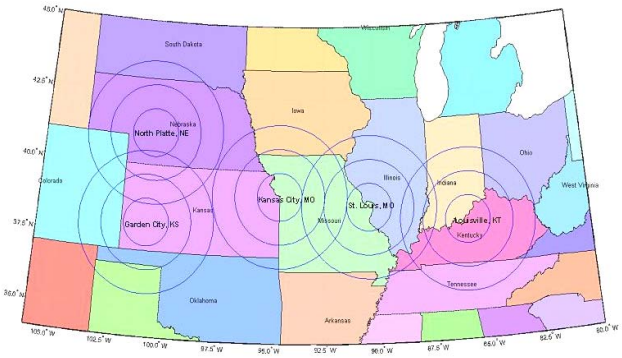

Figure 2: Coverage at 20,000 ft MSL for Prototype Midwest ADS-B System Sensor Sites

- Remote Unit (RU) — enclosure containing a Mode S ES receiver, with an associated antenna
- Miniature personal computer (mini-PC) containing software to (a) control the RU and (b) manipulate information from the RU which is sent to ABESS
- Wide area network components.

The following subsections describe each primary component's hardware/software and functionality, including associated peripherals.

2.2 Remote Unit

Figure 3 shows four of the RU enclosures (prior to their field deployment) that house the Mode S ES receiver, mini-PC, router, and switch. The enclosures and Mode S receivers are pre-production Airport Surface Detection Equipment, Model X, (ASDE-X) multilateration subsystem units, manufactured by Sensis Corp. Figure 4 depicts a dB Systems model 5100A antenna that was deployed as part of each Ground Station. The RUs and antennas used for the Midwest Prototype ADS-B System had been deployed at Memphis International Airport in 2002-03, for an earlier test program.

The RU antenna, receiver, and processor board ingest and detect Mode S ES DF-17 messages. The resulting 112-bit messages are passed, via the network card to the mini-PC described next. In effect, the RU is used as a "pretty dumb" radio. It converts DF-17 messages from modulated radio signals to baseband computer words of the same length, with the Mode S bit-error detection and correction protocol implemented. The RUs have additional capabilities — e.g., partial unpacking of the DF-17 message fields — that were used in the original multilateration test but are not used in this application.

2.3 Miniature PC and Software

The Volpe Center selected the hardware and developed the software for an application-specific mini-PC that (a) controls and monitors the RU; and (b) utilizing the Windows XP Professional operating system, performs most of the processing functions inherent in an ADS-B receiver. Figure 5 shows the mini-PC and Communications Network components. These reside within the RU enclosure.

During system setup or re-configuration, the mini-PC sets several parameters that govern the RUs operation. During normal operations, a "Heart Beat" message is continually exchanged between the RU and the PC. This provides an indication that the system is active when it is monitored remotely.

Software, written in UNIX/LINUX C, accepts 112-bit DF-17 messages from the RU and converts one or more DF-17 messages into a sequence of All Purpose STructured Eurocontrol Radar Information Exchange (ASTERIX) Category 033 (CAT-33)

Figure 3: Four Sensis RU Enclosures

Figure 4: dB Systems 5100A RU Antenna

Figure 5: Mini-PC, Router and Switch

messages ([**5**] contains format details). ASTERIX CAT-33 is the format that will be used for the operational ADS-B system being deployed nationwide. The conversion software runs under Cygwin [**7**], a UNIX-like implementation of the Berkeley Standard Distribution on a Windows/Intel platform. CAT-33 messages are forwarded to the ABESS application via the Communications Network described next.

2.4 Communications Network

Converted CAT-33 data are sent from the mini-PC though a switch to a Cisco 1721 network router in User Datagram Protocol (UDP) format. The data are then transported over a 56 kbps leased line to the UPS Global Operations Center at Louisville, KY. From there, the data are passed over a ½T1 leased line to the Volpe Center. The ADS-B data are then sent over a T1 leased line to the FAA William J. Hughes Technical Center (WJHTC) for fusion with radar data.

The Volpe Center to UPS Global Operations Center connection allows all remote units to be monitored and accessed using Microsoft Windows XP Remote Desktop Protocol. This connection is also used to perform software upgrades and RU configuration changes. Each RU ground stations is a private, isolated LAN with limited allowable IP addresses due to the subnet mask settings.

The Louisville, KY ground station has two significant differences from the other ground stations. This site links to the UPS Global Operations Center through available fiber on the UPS campus. This site also includes a Network Time Protocol with which all equipment installed on the network can be synchronized. This helps to ensure all data are produced using a common time reference. Additionally, software installed on each local PC determines its time based on the polled time and subtracts latencies experienced over the network.

3. System Features

Inter-process communications from the RU to the PC have the potential for adding ever-increasing delays between the receipt of a DF-17 message and the transmission of a corresponding CAT-33 message. However, using socket communications prevents accumulating such delays. This programming and hardware interface also eliminates potential memory leaks that can occur when the operating system cannot keep up with the disk access and interrupt needed for processing a high-volume of DF-17 messages.

DF-17 ADS-B messages broadcast by aircraft do not include a time stamp. Moreover, the Mode S ES receiver in the RU does not assign a time stamp when it receives the DF-17 message. The time stamp assignment occurs in the mini-PC processing software when the message is first received across the socket. This is accomplished by a call to a network time function that returns the number of seconds (including a high-precision fractional part) since a standard "beginning of time" mark. Issues such as message age, expiring time limits, and time between messages are based on this time stamp.

C was chosen as the exclusive language for the processing software due to the availability under Cygwin of the GNU gcc compiler, including libraries for socket communications, advanced mathematics, high-precision calculations, and large array manipulations. Additionally, it provides small compiled executables. If needed in future uses, the processing software C code may be translated for use on any UNIX based operating system, including Linux and modern Macintosh environments.

4. DF-17 to CAT-33 Translation

4.1 Processing Overview

Unlike the situation for the Universal Access Transceiver (UAT) ADS-B version, for the Mode S ES ADS-B version, a single transponder message does not contain all the information needed to form an operationally useful CAT-33 message. Instead, multiple Mode S ES DF-17 messages must be collected before creating a single CAT-33 message. Also, differences between DO-260 and DO-260A compliant transponders are critically important in the DF-17/CAT-33 conversion process.

Many DF-17 message types contain position information; the message type conveys the accuracy of the information. DO-260A-compliant transponder message contain explicit values, found in Type 31 messages, for three data-quality parameters: Navigation Accuracy Category for Position (NACp), Surveillance Integrity Level (SIL), and Navigation Integrity Category (NIC). In contrast, transponders compliant with the earlier DO-260 MOPS provide only a single data-quality parameter: Navigation Uncertainty Category for Position (NUCp). The ways in which navigation data accuracy and integrity are accounted for constitute the major differences in processing DF-17 messages.

The primary data field used to identify all information gathered from a specific aircraft is the 24-bit Mode S ID (also called address). In the U.S., the Mode S ID is permanently assigned to an airframe by the FAA Civil Aviation Registry. It then becomes a unique identifier of that airframe, regardless of flight status or position.

A consequence of having to piece together an output message is that data usage differences must be accounted for and certain design choices must be made in the translation of DF-17 to CAT-33 formats. These include the following:

- *Difference between use of a "zero" value in a DF-17 message and a "zero" value in a CAT-33 message.* In certain fields in a DF-17 message a "zero" value indicates the numerical value of zero, whereas in CAT-33 nomenclature a "zero" value indicates missing or null data.
- *Useful information may "expire" or "go stale" before all of the required data fields are received.* In the code developed for the Midwest Prototype ADS-B System, a configuration file is used to declare when data are "too old" to be considered further (see Section 4.5).
- *Additional processing is required to ensure the correct data-quality parameters are passed to the CAT-33 message.* Because of difference between the two MOPS versions, the NACp/SIL/NIC data-quality parameters available in DO-260A DF-17 message must be inferred from the NUCp and position message type in DO-260 DF-17 messages. In the Midwest Prototype ADS-B System a lookup table is used to implement Table 2-188 on page 613 in [3].

Once the message is passed to the Cygwin process in the mini-PC, the pertinent information is extracted from each DF-17 message. A units/coordinate conversion and format change is performed. A time stamp is used to "time-out" the data if additional fields are not received within the allotted time. When a complete CAT-33 message has been assembled, it is sent onto the network for fusion with radar data.

Figure 6 represents the DF-17 to CAT-33 conversion process. The following subsections describe this process in more detail.

4.2 RU Error Detection and Correction

Once an RU receives a DF-17 message, four preliminary actions are performed on the "raw" data before they can be passed to the PC/Cygwin conversion processes:

1. Setting Confidence Bits
2. Message Determination
3. Message Correction
4. Message Output.

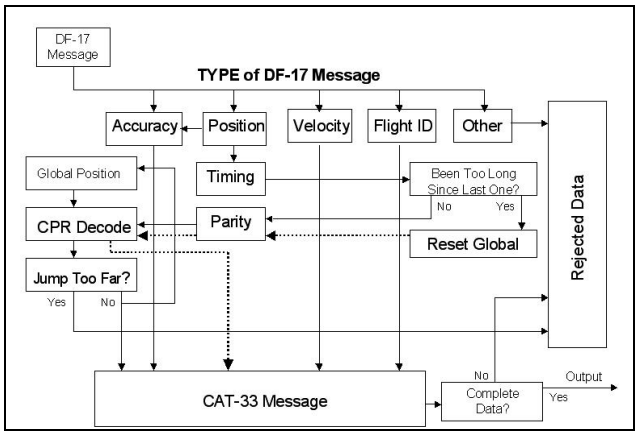

Figure 6: DF-17 to CAT-33 Flowchart with Expiring Data Decision Points

For each received DF-17 message bit, confidence bits are set according to whether the RU receiver has high or low confidence that it has been detected correctly. If the number of confidence bits that are set low — i.e., set to 0, indicating low confidence that the corresponding message bit was correctly detected — is 12 or more, then the entire message is considered to be hopelessly compromised and is rejected. In general, there is no recourse in this situation; the Mode S receiver discards the message and the mini-PC never sees it.

If there are 11 or fewer low confidence bits in a detected DF-17 message, then the RU receiver exercises the Mode S downlink error correction process to switch the most likely errant bits to their correct values. This process is documented in [**6**]. However, even after error correction, there may still be erroneous data present in the output DF-17 message, so that further processing logic must be cognizant of potential latent errors.

Once all error correction has taken place, the RU Mode S receiver sends the corrected DF-17 message to the first step in translation to CAT-33.

4.3 Compact Position Report Decoding

Each DF-17 message is of a particular type (0 to 31), which indicates the content of the data embedded within it. For example: a Type 4 message contains the Flight ID (seven characters) under which the aircraft is currently operating; a Type 19 message contains velocity information; and Types 5-8 contain surface position information.

DF-17 messages of Types 9-18 and 20-22 contain airborne position data formatted as a Compact Position Report (CPR). The CPR format, documen-

ted in [**4**], is used to "shoehorn" high-precision latitude, longitude and altitude information into the limited length message used for broadcast "over the air". Intricate decoding steps are needed to convert a CPR data field to a correct, full-precision word.

Within every CPR is a parity bit and a status bit, indicating whether the CPR data is either "even" (0) or "odd" (1), and whether the aircraft is airborne or on the ground, respectively. CPR data are decoded differently depending on the parity-status combination. Once decoded, and for either airborne or on-ground status, the decoded "even" or "odd" CPR message gives "a third of the picture," for it must be combined with an opposite-parity CPR message and a "base position" to arrive at a unambiguous, full-precision position report. Furthermore, the "even" and "odd" decoding results must be obtained close enough in time so that a "stale" value is not combined with a "fresh" one.

The standards found in [**2** and **3**] indicate that in any 10-sec period there should be, on average, half "even" and half "odd" CPR data within the received set of broadcast DF-17 messages from any given airborne aircraft. However, due to the fragility of the air-to-ground radio link, there will be periods of time when only one kind of parity data survives detection and error correction filtering. The decoding algorithms must take these situations into account, to ensure that long periods of "no data available" do not occur.

When combined, "even" and "odd" parity CPR messages yield a "locally unambiguous" position report, i.e., within a 160 nmi diameter region, the position report is definitive. However, the aircraft may actually be in the same relative position within a different 160 nmi diameter region. Combining the "base position" with "even" and "odd" parity messages results in a "globally unambiguous" position report.

4.4 Rejected Data

Even with data corrections, filtering, and careful decoding of CPR data, it is still possible to generate an incorrect position report. Two ways that this may occur are:

- Errors remain in the detected DF-17 message CPR data after all corrections have been applied by the RU Mode S ES receiver
- A parity bit is incorrectly detected (e.g., an "even" message is mistaken as an "odd").

Regardless of the corruption source, if a decoded position report is not consistent with the aircraft's track — e.g., aircraft "appears" to fly backward, or at a sharp angle sideways — then that position report is discarded in the mini-PC processing.

In practice, such rejected data are rare. The next received DF-17 message almost always supplies acceptable information, which maintains the aircraft track integrity. In the case where there is garbled position information for a significant period of time, that aircraft's track will have gaps corresponding to those time periods.

4.5 Expiring Data

There are three points in the processing flow where previously recorded data may be considered to be too old to be used in future calculations. This "stale" data would then be "expired," i.e., deleted in favor of either no data (the default deletion), or replacement by more current data. These decision points are:

1. Parity data of one kind are too old to be combined with parity data of the opposite kind
2. No useable data has been received from a particular aircraft for a significantly long time
3. The last calculated globally unambiguous position has become too old

Data are expired when one of these situations presents itself during processing of a DF-17 message for a particular aircraft. In other words, an aircraft's previously recorded data are not considered for expiration until new data have been received for that aircraft, at which time these decision points are considered separately. The interaction between these considerations is demonstrated in Figure 6.

4.6 Final Assembly

Once a globally unambiguous position report is available from a DF-17 message and from its context with previously and contemporaneously received DF-17 messages from the same aircraft, a CAT-33 formatted message is assembled from this data and sent to the network.

There is no standard relationship between the number of received DF-17 messages and the number of resulting CAT-33 messages, even for a single

airborne aircraft. Depending on the quality of the received signal, the Type of DF-17 messages, the mixture of parity data, and the timeliness of the required elements, the CAT-33 messages may not be available under any particular schedule or guaranteed rate.

5. ADS-B/Radar Data Fusion

Each ground station's CAT-33 ADS-B message stream is sent to the FAA WJHTC for fusion with radar data. Radar fills in gaps in ADS-B coverage and allows tracking of non-ADS-B aircraft. The radar data are received over the Federal Telecommunications Infrastructure (FTI) service in En Route Communications Gateway (ECG) format. Five en route radars are utilized:

- Garden City, KS (GCK)
- Croker, MO (QJN)
- Omaha (Offutt AFB), NE (QHO)
- Chelsea, OK (QAF)
- Lusk, WY (LSK).

Coverage for the en route radars (each having a nominal range of 250 nmi) is significantly greater than that for the ADS-B sensors (each having a nominal range of 150 nmi). Figure 7 depicts both ADS-B and radar coverage — note that pink denotes overlapping radar/ADS-B coverage.

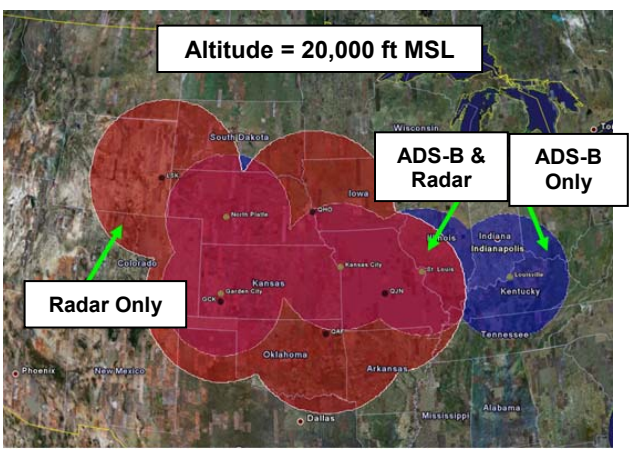

Figure 7: ADS-B and Radar Coverage Areas

Radar and ADS-B data are ingested into a Sensis Corporation Multi-Sensor Tracker (MST) which fuses the information. The MST tries to associate an ADS-B track with a radar track using 3D position information (latitude, longitude and altitude).

Additionally, the MST fuses multiple radar tracks for the same aircraft if the aircraft is within a region of overlapping radar coverage. While the primary fusion mechanism is the 3D position information, the Mode 3/A beacon codes provided by the radar are also used. The MST output messages also follow the CAT-33 format.

Each output radar track is assigned a unique track file identifier. This identifier is used by the MST to associate new radar reports. When fusion occurs between ADS-B and radar, the MST includes all relevant target information — e.g., 12-bit beacon code, 24-bit Mode S address, flight ID, etc. However, when only one sensor type is available (radar or ADS-B), the output information is limited to that available from the sensor involved.

6. Processing Radar-Only Reports

MST output messages for radar-only data lack a flight ID. Similarly, ADS-B-only messages lack the beacon code. The former is much more critical for this application, as ABESS processing is based on aircraft flight ID.

The solution — interim, in that it will not be needed when ADS-B is fully deployed — devised for this effort is to use an additional data source, the Traffic Flow Management Data to Government (TFMDG) feed from ETMS. The TFMDG feed is comprised of the entire ETMS NAS data set collected from all the Air Route Traffic Control Centers (ARTCCs) and selected Terminal Radar Approach CONtrol (TRACON) facilities. TFMDG position data are not used because, at once per minute, the updates are too infrequent. However, TFMDG data provide a link between beacon codes and flight IDs.

The TFMDG feed data feed is generated at the WJHTC, and contains eleven types of messages.

1. Beacon Code Information
2. Arrival Notice
3. Departure Notice
4. Flight Plan
5. Flight Plan Cancellation
6. Center Boundary Crossing
7. Flight Plan Amendment
8. Track Information
9. Oceanic Report
10. Flight Management Information
11. Heartbeat

Each TFMDG message includes flight ID, time (UTC), and the associated ATC facility (ARTCC or

TRACON). TFMDG messages are sent in compressed Extensible Markup Language (XML).

Figure 8 depicts the process, performed at the WJHTC, for adding flight IDs. Beacon codes from MST radar-only messages are compared to beacon codes found in the TFMDG data feed. Upon finding a match (which is verified by close agreement of the position data), the associated flight ID is placed in the MST CAT-33 output message. The message's length and User Application Profile (UAP – the header) are modified to complete the message change.

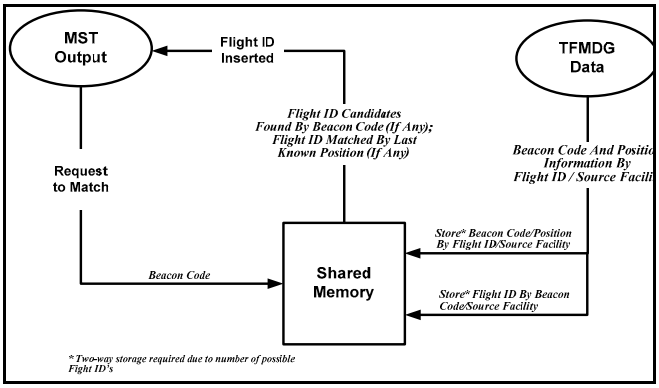

Figure 8: Processing for Assigning a Flight ID to a Radar-Only Message

Radar reports and the TFMDG data are matched from a shared memory table which includes flight IDs, facility centers, beacon codes, latitude and longitude of last track update, and time of information receipt. Data from the table are adjusted based on changes in beacon codes, flight plan cancellation, and track information messages.

The shared memory table, accumulating the TFMDG data, uses the flight cancelations messages to expire an entry. Every beacon code and flight cancelation message includes the originating and destination airports. If the cancelation message received includes the destination airport the entire entry is removed.

7. Example ADS-B Data

Before the CAT-33 data from the ground stations are sent to the WJHTC for fusion, the data is passed through the Volpe Center and recorded. The data can be display real-time or stored on a local PC for later use.

The recorded stream of CAT-33 messages can be straight forwardly decoded, not requiring any elaborate decoding process. Unlike the CPR decoding used on the raw DF-17 messages, the latitude and longitude can easily be converted into a decimal value. Individual aircraft tracks are readily displayed on a map — see Figure 9.

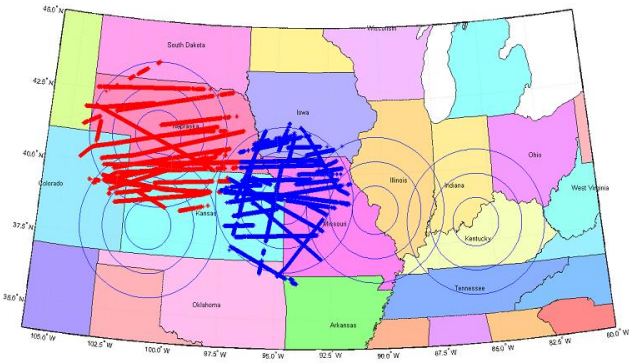

Figure 9: Aircraft Tracks from Two ADS-B Sites

The CAT-33 messages may be further filtered by call sign, altitude, or other identifying characteristic, to select only the messages of interest.

8. Lessons Learned

The Midwest Prototype ADS-B System ground stations can be configured to only output CAT-33 reports for UPS aircraft (the operational mode). The data field used to identify UPS aircraft is the 24-bit Mode S ID embedded in the DF-17 message. The Mode S ID is well-suited to this role, as it is unique and permanently assigned to an aircraft, regardless of flight status or location.

If there is an error in the Mode S field that is not detected in the RU or mini-PC processing, then it will be misidentified in the CAT-33 message, since there is no further error correction mechanism available for this data field. In practice, with a properly calibrated receiver, this rarely occurs, so that data lost due to misidentified Mode S IDs are an unavoidable, yet acceptable, risk.

Once an aircraft has been correctly identified, a determination must be made as to whether data have been received "too late" to be validly combined with a previously decoded set of data for the same aircraft. In general, the amount of time separating two validly combined data sets for a given aircraft depends strongly on the quality of the data being received.

When the Mode S ES receiver that constitutes the "front end" of a full ADS-B receiver encounters a high percentage of DF-17 messages that cannot be detected correctly, one or both of two undesirable situations occurs: very few CAT-33 messages are generated, and/or the position reports are highly erratic, since more widely separated data are combined to produce the globally unambiguous position reports. Tuning the Mode S ES receiver so that it outputs as little data as possible with low confidence bits is a productive use of system engineering effort. For the Sensis RUs used here, the receiver Minimum Threshold Level (MTL), which sets the threshold of the received signal, was beneficially increased to cause weaker signals to be ignored.

To avoid delays in processing a DF-17 message once the receiver has completed its processing, the utilization of inter-process socket communications is absolutely necessary. In fact, introducing any other processing interface between the receiver and the network created an accumulating delay in the time between signal receipt and CAT-33 message generation. It was found that "large" applications such as MATLAB and general-purpose utility codes actually introduced large delays (on the order of 30 minutes. even after only a few hours of operation), and their use had to be abandoned.

During processing to create the CAT-33 message, it is critical to keep track of the times when DF-17 messages are received. Transponder DF-17 messages do not contain time stamps, so the decoding and CAT-33 message assembly processing must assign a "time of receipt" once the DF-17 message has come across the communications socket from the receiver. Time accounting must be separately maintained for each aircraft so that "stale" data may be excluded from calculations. Figure 10 shows a stable track across the coverage regions for four ADS-B ground stations.

Time stamps must be recorded for each receipt of: an even parity position report; an odd parity position report; the velocity, heading, and other dynamic flight information; accuracy and integrity information; and the flight ID (even though this data item does not change very often).

As is often the case when multiple factors are simultaneously under consideration, the interplay between timestamps must be carefully considered. When an even parity position report "goes stale," the question occurs: Is the most recently received

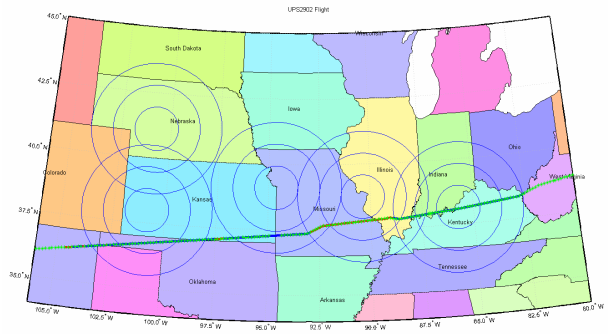

Figure 10: Aircraft Track through Multiple ADS-B Ground Station Coverage Regions

odd parity position report automatically considered "stale" as well, regardless of how recent it is — i.e., do the calculations start completely "from scratch" if there are any missing data for a significant period of time?

If so, then there will likely be relatively long periods where there are no CAT-33 messages produced. However, those few position reports that are produced will be almost certainly without error. Or is each time stamp evaluated independently of all others, so that "going stale" on one time stamp does not affect the inference available from the other time stamps? These issues may be addressed by choosing/using appropriate values in the DF-17/ CAT-33 translation code.

The approach taken in the Midwest system is if the recorded position data go stale, we continue to utilize the last calculated globally unambiguous position until a new globally unambiguous position is calculated from scratch, i.e., from new data that have been received since the stale data were detected. However, this may not be the best way to proceed. Our intent here is to raise questions about what decisions need to be made, not which choices are best.

Using the ADS-B ground station as the "base position" for establishing a "globally unambiguous" position from the CPR data — a common practice — can lead to wild swings in calculated position when an aircraft is near the boundary between two 160 nmi diameter regions. For example, a newly received "even" parity position report might place the aircraft at the extreme western edge of one region, while the next "odd" parity position report might place the aircraft at the extreme eastern edge of the same region, when it is intended that the eastern edge of the adjacent region be used.

However, since each DF-17 message is independent of all others, the CPR encoding does not communicate such context information. If used literally, successive CAT-33 messages would have the target swinging 160 nmi back and forth between the two parity solutions.

A related problem occurs near the boundary between two 160 nmi diameter regions when an aircraft track closely parallels the boundary. Then "stitching" can occur when one parity data puts the position on one side of the border while the other parity data puts the position on the other side.

A solution to these common anomalies may be found by using the last known globally unambiguous position of the aircraft as the "base position." Each individual aircraft has its own "base position," depending on previously received data, rather than using a single, static "base position" for all aircraft. With this method, the base moves every time a globally unambiguous position is found, so that it is never very far from the aircraft's current position when a new DF-17 position report is received. In fact, as long as the position of the aircraft is within 80 nmi of the last known globally unambiguous position when new position data arrive, then stitching or wild swinging of position reports are not possible.

Since an aircraft traveling at 600 kt covers 80 nmi in 8 min, as long as "fresh" parity data is not combined with "stale" parity data that is more than 8 min old, then using the last known globally unambiguous position as the "base position" in the CPR decoding will ensure stability in an aircraft's displayed track. Our experience is that ADS-B data for an individual aircraft are very rarely separated by more than a few seconds, unless the aircraft is entering or leaving a sensor's coverage region.

In general, expiring "stale" data to ensure that different parity data are combined in a meaningful way will guarantee accurate position reports from the CPR decoding process. Under which circumstances and under exactly which analytical rules to expire old data is a fine-tuning exercise best undertaken once the ground station Mode S receiver has been calibrated to provide high-quality DF-17 messages for conversion to CAT-33 messages.

The lack of a 12-bit beacon code in CAT-33 messages generated from ADS-B DF-17 messages is not an issue for the ABESS application. However, these target reports could not be utilized by current NAS automation systems, which employ the beacon code to distinguish individual aircraft.

Lastly, under the DO-260 MOPS, there are approximately 10 accuracy and integrity combinations that the transponder may provide via the DF-17 message type and NUCp parameter. In contrast, under DO-260A, a transponder may provide approximately 1,000 accuracy-integrity combinations via the NACp/SIL/NIC parameters. Thus a DO-260A transponder may communicate with much greater precision the confidence with which an application may use the navigation data. Furthermore, using DO-260A, there is no need to implement a lookup table or other inference methodology, which streamlines the translation process.

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2008 ICNS Conference

5-7 May 2008