Demonstration of GPS Automatic Dependent Surveillance of Aircraft Using Spontaneous Mode S Beacon Reports*

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BIOGRAPHIES

The authors are staff members at MIT Lincoln Laboratory and are currently working on the ADS-Mode S program in the Air Traffic Surveillance group.* Ed Bayliss has five years of satellite navigation experience including work on GPS-GLONASS, RAIM, and recently was lead engineer on the DGPS-Mode S Special Category I precision approach demonstration program. He served on the RTCA team that wrote the DGNSS Instrument Approach System standard. Bob Boisvert is lead engineer for the ADS-Mode S demonstration at Hanscom Field and has over 10 years of radar systems experience. George Knittel is currently serving as ADS-Mode S program manager, is a private pilot, and has expertise in radar systems, antennas, and electromagnetics.

ABSTRACT

A new Automatic Dependent Surveillance† (ADS) system concept combining GPS satellite navigation with Mode S data communications is described. Several potential applications of this concept are presented with emphasis on surface surveillance at airports. The navigation and data link performance are analyzed. Compact ADS position formats are included. The results of the first tests at Hanscom Field demonstrating the feasibility of the spontaneous broadcast of ADS positions using Mode S messages are presented. Test aircraft, vehicles, avionics equipment and the ground system configuration are described. Avionics standards and GPS interface requirements are discussed. Multipath and airport surface coverage issues are addressed. Plans for further testing in an operational environment at Logan Airport are outlined.

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† ADS (Automatic Dependent Surveillance) is a generic term used for years in the aviation community to denote regular, automatic position reports from aircraft based on their internal navigation system equipment.

INTRODUCTION

Background

The International Civil Aviation Organization (ICAO) has defined a concept for communications, navigation, and surveillance for the next century known as the Future Air Navigation System (FANS). The subject of this paper, ADS-Mode S, uses two of the four key technologies identified by the FANS panel. They are the Global Navigation Satellite System (GNSS) and the Mode S beacon system. Both the U.S. system, GPS, and the Russian system, GLONASS, have been made available for use by the international civil aviation community free of charge. The Mode S secondary surveillance radar (SSR) system is an improvement to the older radar beacon systems† in that it makes use of a discrete address for each aircraft transponder. Mode S technology is also the basis for the collision avoidance system (TCAS) now installed on most U.S. air transport aircraft as well as the Mode S data link system, which will be part of the Aeronautical Telecommunications Network (ATN).

ADS-Mode S is a system concept [1] utilizing the frequencies and formats of the Mode S system for downlinking position information and also uplinking differential GNSS corrections. The result is an integrated concept for surveillance that permits aircraft equipped with a Mode S transponder and a GNSS receiver to participate in both ADS and SSR environments. This makes possible a smooth transition of the National Airspace System (NAS) surveillance system from a beacon-based to an ADS-based environment.

In the fall of 1992, the FAA asked MIT Lincoln Laboratory to demonstrate the application of Mode S data link to the DGNSS Instrument Approach System (Special Category I), which culminated in a successful demonstration in April 1993 of omnidirectional broadcast of

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† Older Air Traffic Control Beacon Interrogators (ATCBI) did not use addresses for interrogations, resulting in overlaid or garbled replies from closely spaced aircraft.

DGPS corrections using Mode S [2]. At about the same time, the FAA's Beacon Interrogator Replacement Study committee was examining ADS as an alternative for replacing the aging SSRs remaining after implementation of 133 Mode S radars [3]. Earlier, in March 1992, a proposal by Paul Drouilhet of Lincoln Laboratory had identified Mode S squitter of GNSS position as a candidate for ADS. These were the steps that led to the current project: ADS-Mode S [4].

Objectives

While the initial interest in ADS-Mode S was for air surveillance, an even more pressing problem is that of surface surveillance at airports. Therefore, the objectives of the current project are to demonstrate the basic elements of surface ADS-Mode S: first, in a Squitter Proof-of-Concept Evaluation, which took place in August 1993 at Hanscom Field, and later, at Logan Airport in Boston. In particular, the principle objectives are as follows:

- Demonstrate the feasibility of long squitter modifications for reporting ADS positions.

- Determine squitter reliability on 1090 MHz with respect to coverage and interference.

- Determine the value of multiple sites for filling gaps in coverage.

- Determine DGNSS uplink reliability on 1030 MHz using multi-block protocol.

- Confirm that DGNSS accuracy is sufficient for surface ADS reporting.

- Demonstrate surface ADS display options.

The Proof-of-Concept Evaluation was a preliminary look at the essential elements of surface ADS-Mode S. It identified several issues that will be addressed in the Operational Suitability Assessment scheduled to take place at Logan International Airport, Boston, in February 1994.

Motivation

The benefits of GNSS for aircraft navigation are logical and rapidly coming to fruition. The next step to leverage its benefits is to couple it to a ubiquitous widely available data link such as Mode S. With 16,000 transponder units in the field and about 20 being sold each day, Mode S has become a widely used avionics device. Mode S offers an evolutionary systems approach to introducing new technology that does not require the "Big Bang" of a totally new system. There are a number of significant benefits from combining GNSS with Mode S:

- *No Frequency Spectrum Problems.* The Mode S system is accepted internationally and its frequencies are available worldwide. In the US it is owned and operated by the FAA with no user fees. Use of Mode S for ADS would add less than 0.1 percent to current channel occupancy.

- *Smooth Transition from SSR to ADS.* As aircraft are equipped with GNSS sets, the interface to Mode S

transponders will give immediate ADS benefits. Transponder modifications are minimal and estimated to add less than 5 percent to transponder cost. Costs both to the user and the FAA are low.

- *Single Avionics Transponder Supports Multiple Uses.* A single transponder will support both SSR interrogations and ADS reports. In addition, it provides a high speed[†] two-way data link for real-time applications such as: DGNSS corrections, ATC alerts, and traffic information.

- *Standards Exist for Mode S and TCAS Equipment.* Existing standards for performance and interfaces would require only minor modification to add the ADS long squitter.

- *ADS Ground Stations Based on TCAS Components.* TCAS components which are small and low cost relative to other ground-based surveillance equipment would be used to construct ADS ground stations. Relatively large production of TCAS units (i.e., 6000 units) gives a realistic cost projection.

SYSTEM CONCEPT

ADS-Mode S System Components

The basic ADS concept is that the Mode S transponder on each aircraft will automatically broadcast the aircraft's GNSS location twice per second. The broadcast feature allows a "party line" (e.g., Local Area Data Link) where both controllers and pilots will have access to the surveillance data they need. For surface or approach applications, where better accuracy is required, the aircraft will also receive DGNSS corrections broadcast from the ground (or Wide Area DGNSS when available) with which to correct its GNSS position.

On the aircraft, ADS-Mode S can be implemented by some relatively straightforward modifications to Mode S transponders that are already onboard most air carrier aircraft and will soon be available for general aviation.

On the ground, the equipment that needs to be installed is also based on subsystems and components that are already in production. The concept drawing (Figure 1) serves to illustrate the types of installations that are envisioned. Three areas of service are envisioned: airport surface ADS (3-nmi range), small terminal areas (50-nmi range), and en route (100-nmi range).

Airborne Equipment

Current Mode S transponders broadcast their Mode S address spontaneously once per second (called a "squitter") in order to identify themselves to TCAS-equipped aircraft. The actual spacing between squitter transmissions is randomized to avoid synchronous interference.

[†] In addition to providing ranging data to the secondary surveillance radar, Mode S provides a system for transfer of data packets of up to 112 bits in both directions: uplink at 1030 MHz at 4 Mbps and downlink at 1090 MHz at 1 Mbps.
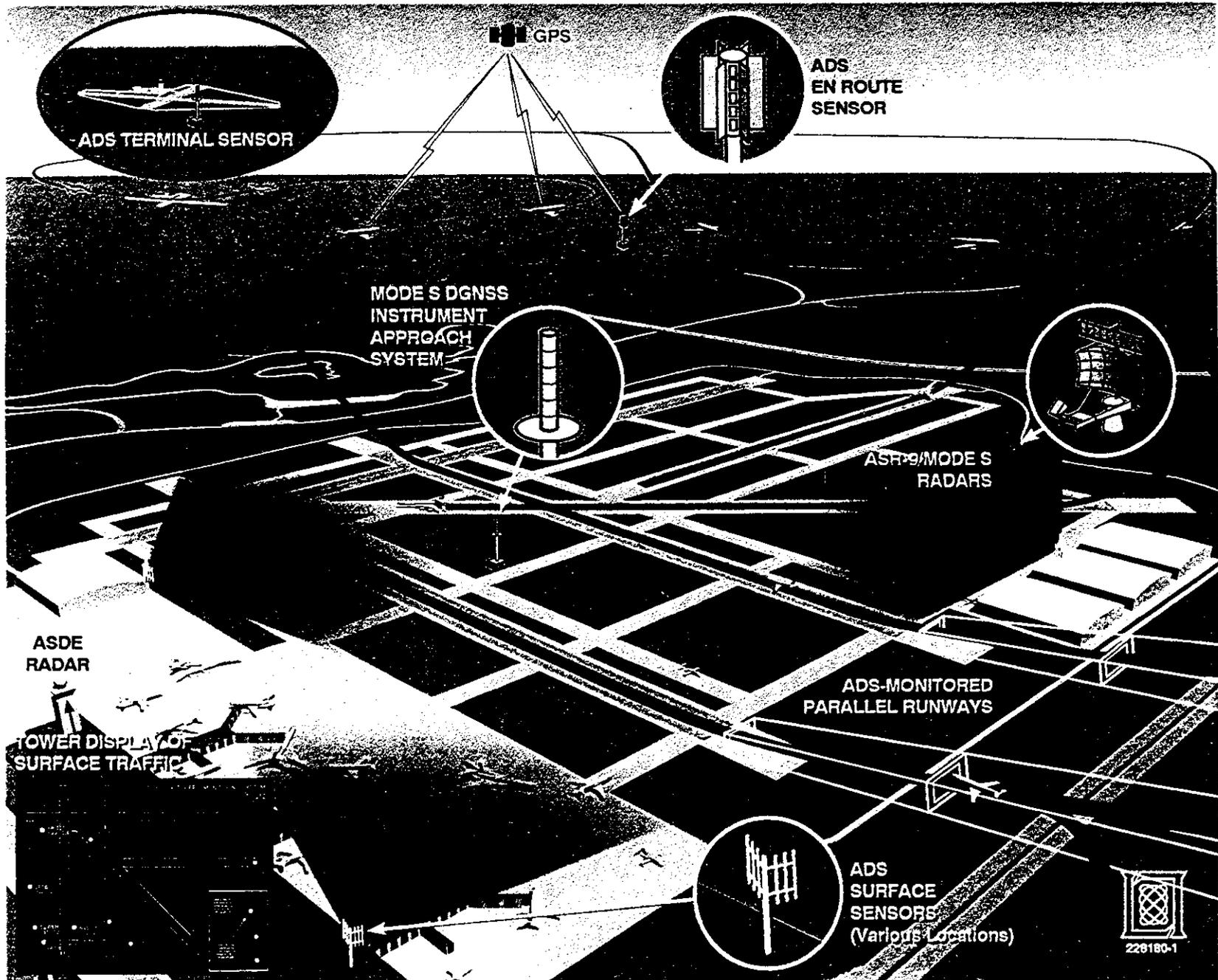
GPS

ADS TERMINAL SENSOR

ADS
EN ROUTE
SENSOR

MODE S DGNSS
INSTRUMENT
APPROACH
SYSTEM

ASR-9/MODE S
RADARS

ASDE
RADAR

ADS-MONITORED
PARALLEL RUNWAYS

TOWER DISPLAY OF
SURFACE TRAFFIC

ADS
SURFACE
SENSORS
(Various Locations)

226180-1

Figure 1. ADS-Mode S System Concept using Mode S to broadcast GNSS airborne positions and DGNSS surface positions.

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Transponders also have the capability to store 256 56-bit registers of data which are intended to be transmitted on request to either ground interrogators or (eventually) TCAS units. All registers are loaded over a data link port as currently specified in the standard RTCA/DO-181A. It is a relatively small modification to include one of these registers in the twice-per-second squitter. Thus, Collins was able to deliver a modified transponder in May 1993, one month after contract award.
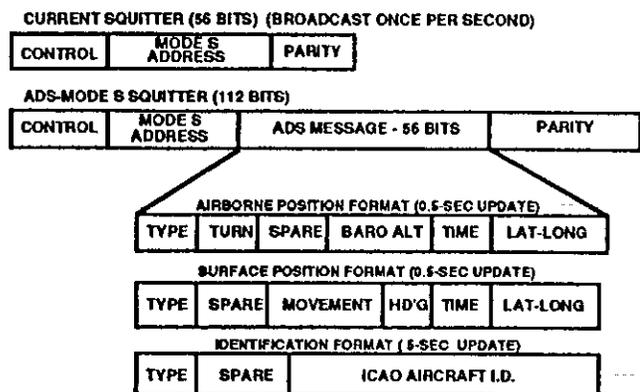
CURRENT SQUITTER (56 BITS) (BROADCAST ONCE PER SECOND)

CONTROL	MODE S ADDRESS	PARITY

ADS-MODE S SQUITTER (112 BITS)

CONTROL	MODE S ADDRESS	ADS MESSAGE - 56 BITS	PARITY

AIRBORNE POSITION FORMAT (0.5-SEC UPDATE)

TYPE	TURN	SPARE	BARO ALT	TIME	LAT-LONG

SURFACE POSITION FORMAT (0.5-SEC UPDATE)

TYPE	SPARE	MOVEMENT	HD'G	TIME	LAT-LONG

IDENTIFICATION FORMAT (5-SEC UPDATE)

TYPE	SPARE	ICAO AIRCRAFT I.D.

Figure 2. ADS-Mode S Long Squitter Format.

The current 56-bit squitter containing a control field, a Mode S address field, and a parity field will continue to be broadcast at 1090 MHz at an average rate of once per second. The GNSS data are loaded into two of the transponder data registers—one in the airborne position format (register 5) and the other in the surface position format (register 6). The transponder squitters the appropriate register based on a landing gear (i.e., "squat") switch. The standard ICAO Aircraft ID register (32) is also squittered, but only every 5 seconds (±0.2 seconds) to identify air carrier flight numbers. Long squitter messages will use a new downlink format (i.e., DF=17). Details of these formats can be found in the Appendix.

With only 56-bits, it was a challenge to encode a seamless position report with 5-meter precision that could be decoded without ambiguity. To conserve bits, position was reported on the UTC second so only 1 bit was needed for time. While GNSS velocity can be used to extrapolate the position to the nearest UTC second, future GNSS receivers should be built so that they provide aircraft position exactly on an integer UTC second. Higher order time bits are restored by the receiving station.

The Mode S transponder is designed to interface to an airborne data link processor (ADLP) through the data link port. The ADLP filters messages, sending ATN messages through the ISO 8208 interface to the ATN router and sending real-time, broadcast messages through the Mode S special services port to applications such as the DGNSS receiver [5]. In the absence of the ADLP, the GNSS receiver could interface directly to the Mode S transponder data port.

The AEEC has developed interface standards for the air transport GNSS receiver (ARINC Characteristic 743A). These units provide GNSS or DGNSS positions every second on the output bus. A supplement has been added to describe the DGNSS corrections. DGNSS corrections destined for the GNSS receiver are to be formatted according to Appendices A and G in the MASPS [6].

Aside from business aircraft, very few general aviation aircraft are equipped with Mode S transponders. Currently, only one vendor offers a panel mount transponder (about $2700). Lincoln Laboratory is working with Bendix/King to upgrade this transponder to have data link capability (i.e., Mode S level 3). This would support uplinking of DGNSS, TIS, and GWS messages (described later). The ADS squitter will also be added to this unit at the same time.

There are a number of general aviation GPS receivers, some of which will receive certification under TSO C129 for supplemental navigation. Some receivers can also accept DGPS corrections and may be approved for Special Cat I Precision Approach. These receivers would also support the accuracy needed for ADS Surface Surveillance.

Ground Station Equipment

ADS-Mode S for airport surface surveillance needs only a short range of a few miles. Since this is well within the nominal 10 nmi range of TCAS equipment, few modifications will be needed to accept long squitters. A typical airport (e.g., Figure 1) is expected to require from two to four ADS surface sensors (called Ground Interrogator-Receiver Units—GIRUs) in order to cover movement areas (runways and taxiways) using directional antennas situated to avoid interference from multipath.

ADS-Mode S for air surveillance will need a greater range than TCAS. Receiver sensitivity can be improved by about 10 dB by reducing the minimum threshold level in the receiver. (This may require a low-noise figure pre-amplifier.) Transmit range can be extended by adding a 3-kW final amplifier. These basic modifications, plus two new antenna designs, would accommodate both the terminal area and en route configurations.

The ADS terminal sensor (omnidirectional GIRU) can be designed using a 4-dBi omnidirectional antenna with a 5-ft vertical aperture to provide air surveillance as well as deliver uplink messages to a 50-nmi range for small and medium-sized terminal areas. (Note: large terminal areas are covered by Mode S SSRs.)

The air surveillance ADS terminal sensor (GIRU) can also be used to provide uplink for a DGNSS Instrument Approach System (DIAS). A GNSS reference station would be located somewhere near the airport in order to provide differential corrections to all GIRU stations. One such unit should be able to provide DGNSS corrections for both surface surveillance and DIAS. Also, because an integrity monitoring station is provided as part of the DIAS function, it may not have to be duplicated for the surface ADS system. The reader is referred to description the DIAS system [2] and the MASPS [6].

The air surveillance ADS en route sensor (sector GIRU) modifies the terminal GIRU to achieve a 100-nmi

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range. Six 60-degree sector antennas would be used to increase the gain to 8 dBi. Each sector has an independent low noise receiver while the transmitter is switched between sectors. The 6-sector design has the added benefit of dividing the surveillance areas so higher aircraft densities can be handled.

ADS System Applications

Surface Surveillance

Safety of aircraft on the surface, one of the primary concerns of the FAA, has received high priority in the light of several accidents in the last few years. To eliminate these "runway incursions," it is important for tower controllers (and perhaps pilots) to have high quality surveillance of aircraft and vehicles. In 1990, there were 278 incidents reported where there was the potential for high-speed collision [7]. About half these reports were in good weather.

Improved primary radars (Airport Surface Detection Equipment—ASDE) now being installed at 29 major airports will help greatly in bad weather. However, they do not provide aircraft/vehicle identification, thus allowing possible confusion of aircraft.

ADS-Mode S would provide the aircraft identification as well as its location. These data can be merged with the ASDE surveillance. The uplink feature of ADS-Mode S handles DGNSS corrections to achieve an accuracy of 2-5 m. This meets the requirement for identifying aircraft with their positions on the taxiway.

In order to detect when an aircraft starts its take-off or starts to roll across an active runway, either a high update rate or an onboard detection of acceleration is required. ADS-Mode S uses both a high update rate as well as a message field that flags acceleration and aircraft heading.

Air Surveillance

The FAA has 252 aging ATCBIs which are slated for replacement by 2000. Generally, these sites do not need to support aircraft densities as high as that at the 133 Mode S sensor sites now being deployed. One of the first applications ADS-Mode S was considered for are these low density sites, with the possibility of additional sites as "gap fillers" where the main Mode Sensors cannot provide low-altitude coverage.

Air-to-Air Surveillance (CDTI)

Visual display of nearby aircraft has been found to be helpful to pilots in maintaining situational awareness. This feature is called CDTI: Cockpit Display of Traffic Information and is similar to traffic information service (TIS). ADS-Mode S could serve as a basis for CDTI. Simply by listening to the ADS reports on the "party line" an aircraft could determine position of nearby aircraft allowing traffic to be presented on a CDTI display. A 1090-MHz receiver would be needed to receive ADS traffic reports.

Traffic Alert and Collision Avoidance System

The Traffic Alert and Collision Avoidance System (TCAS) is a safety system that "backs up" the normal ATC system and flight rules. The current implementation of TCAS 2 does not have sufficiently accurate bearing to resolve potential conflicts with horizontal maneuvers; it must resort to "climb" and "descend" directives. ADS-Mode S gives much better bearing accuracy which could permit horizontal resolution of potential conflicts (i.e., TCAS 4). In addition, most of TCAS operation could be done passively, using active interrogation only to negotiate a resolution maneuver with the conflicting aircraft via exchange of accurate GNSS velocity, heading, and intent data.

Related Mode S Applications

DGNSS Instrument Approach System

The first DGPS application using Mode S was a Special Category I (SCAT-I) Precision Approach, demonstrated in April 1993 [2]. System standards for DIAS have since been refined and are now being promulgated by the RTCA [6]. This demonstration used the same omnidirectional ground station uplink now being tested with surface ADS. A Trimble TNL-2100 DGPS receiver was used to guide the aircraft during precision approaches.

Because the DGNSS uplink functions are similar to those of surface ADS, some of the system components or subsystem designs can be shared.

DGNSS Precision Runway Monitoring

If the DIAS is implemented at an airport, any aircraft with ADS-Mode S equipment would be reporting DGNSS corrected positions as it flies the precision approach. For airports with parallel runways that meet certain separation criteria, this would permit them to gain capacity by using runways independently, even in bad weather. Currently, this function can be supported only at airports that have special high-rate SSRs.

Data Link Functions

There are a number of data link functions that the Mode S data link is designed to support [8]. The availability of these and other ATN services using the same equipment needed for ADS-Mode S is viewed as an added incentive to equip, particularly for general aviation (GA) aircraft.

There are several services envisioned as part of ASTA-3 [7] that make use of the two-way data link:

- *Surface Traffic Data* can be sent directly to each equipped aircraft to display, not only ADS aircraft, but other surface aircraft and vehicles as well. This function is similar to TIS below.

- *Direct Cockpit Alerts* of potential surface conflicts can be delivered rapidly directly to the pilot over the link.

- *Active Taxi-Route Guidance* can be delivered over the data link, thus relieving the congestion often experienced on VHF voice channels.

Traffic Information Service (TIS) provides traffic data in a manner analogous to TCAS and CDTI discussed above. All nearby traffic is uplinked over Mode S. It is particularly useful for GA aircraft that lack TCAS and might be useful during a transition to ADS-based CDTI before all aircraft are ADS equipped. This is an experimental service developed and tested on a production Mode S sensor operated at Lincoln Laboratory.

Graphical Weather Service provides for uplinking compressed weather maps on request over the Mode S data link. This allows the pilot to request weather maps not only for his immediate vicinity, but also for a remote destination. Access to weather radar products while in the air is a service that is very desirable, particularly to GA pilots who do not have weather radars. Special map compression techniques allow transmission of a typical weather map in one 1280-bit Mode S extended length message.

System Performance Analysis

Squitter Downlink Performance

The ground stations for both surface and air ADS will likely be based on equipment developed to implement TCAS on aircraft. This technology is smaller, cheaper and much less complex than that used in large, rotating-antenna Mode S sensors. Each TCAS-based ground station will contain a 1090-MHz receiver, and a 1030-MHz transmitter that can be controlled to produce peak power between 10 and 500 watts. Airport surface surveillance ranges can be easily handled by the equipment because it was designed to operate at a range of 10-14 nmi.

Air surveillance requires greater range performance. About a 50-nmi range is needed for a terminal area while a 100-nmi range is expected to be needed for en route coverage. The range can be extended with a low noise receiver—giving a 10-dB improvement over TCAS (see Table 1). Adding a 5-ft cylindrical antenna will restrict the elevation pattern and add about 4 dB of gain giving an omnidirectional system with a 50-nmi range. In order to achieve the 100 nmi for en route ADS, a 6-sector antenna is used to get another 4.5 dB of gain. Each of the 6 antennas will require its own receiver and signal processor. This increases the probability of detection by reducing interference from competing signals.

Table 1. Squitter Downlink Power Budget

System Parameter	TCAS	Terminal Omni	Enroute Sector
Transponder			
Power (dBm)	54	54	54
Antenna Gain (dBi)	0	0	0
Path Loss (dB) for:	-118.5	-132.5	-138.5
Range, nmi	10	50	100
Receiver			
Antenna Gain (dBi)	0	4	8.5
Cable Loss (dB)	-3	-2	-2
Power (dBm)	-67.5	-76.5	-78
Min Detect. (dBm)	-77	-87	-87
Link Margin (dB)	9.5	10.5	9

Reception on an airport can be subject to deep fades due to ground bounce multipath over the smooth reflective surface. By placing the surface ADS antenna high enough to keep the path difference greater than $\lambda/12$, fades greater than 6 dB can be avoided. Placing the antenna at 50 ft or greater is feasible and avoids fades at ranges out to 2 nmi for all but the lowest aircraft (i.e., < 9 ft). Multipath from terminals and hangers also causes self interference. In order to avoid this, antennas will be placed on the terminals looking away from large structures. This requires directional antennas with reduced fields of view (e.g., 60-270 degrees). Because of multipath and shadowing, any complex airport will require multiple antennas to increase coverage and gain spatial diversity. It is estimated that Boston's Logan Airport will require about 4 antennas to cover all movement areas [9].

The number of aircraft that can be accommodated by an ADS-Mode S system is limited by the amount of competing activity on the 1090 MHz downlink frequency. This frequency is limited to secondary surveillance radars including ATCRBS (Air Traffic Control Radar Beacon System) with 20 µs replies and Mode S with short (64 µs) replies as well as Mode S data link with long (120 µs) messages. For this capacity, analysis a moderately high ATCRBS reply rate of 60 replies per aircraft per second is assumed (Table 2). Because of the design of the Mode S waveform, these replies will interfere with ADS squitter only if they are stronger. Thus, the longer the detection range desired, the more of these replies that will cause interference. The number of competing replies can also be limited by using a sector antenna. This will reduce the competing interference by a factor equal to the total omnidirectional replies divided by the maximum number seen by any sector.

Table 2. Squitter Capacity Analysis

Parameters	Surface ADS		Air ADS	
	Omni	Direct'nal	Omni	Sector
System				
Integration Period	1.2 s	1.2 s	5 s	5 s
Det. Prob. Req'd	97%	97%	99.5%	99.5%
Det. Range, nmi	2	2	50	100
Antenna				
Field of View	360°	140°	360°	60°
Elevation Angle	-16°	-16°	7°	7°
Interference				
ATCRBS (20µs)	0	0	60	60
Mode S (64 µs)	0	0	8	8
Mode S (120 µs)	0	0	6	6
Chan. Occupancy, µs	0	0	2672	2672
with ADS Mode S,µs	264	264	2963	2963
Interf. Range, nmi	6	6	150	250
Interf. Altitude, kft	2	2	43	43
Reduction Factor	-	2	-	2.5
Capacity, Aircraft	250	500	140	350

The capacity in terms of the number of aircraft is determined by computing the probability that the long squitter will be correctly received in the allotted integration period. The probability that a squitter will be received is the probability that there are no Mode S replies and, at most, one ATCRBS reply that falls, even partially, into a window of 120 µs when the squitter is to be received. This is modeled as a Poisson process where each additional aircraft adds the amount of interference shown in Table 2. Because a squitter is transmitted every 0.5 second (±0.1 seconds) there will be two opportunities in 1.2 seconds for Surface ADS and approximately nine opportunities in 5 seconds for Air ADS. In the case of directional antennas which restrict the field of view, there will be an additional reduction factor which depends on how evenly targets are distributed. We assume a reduction factor of 2 for the 140-degree directional surface antenna and a reduction factor of 2.5 for the 60-degree air sector antenna. The resulting integrated detection probabilities vary with the number of aircraft as shown in Figure 3.

Providing a 97 percent probability of updating an aircraft's position every 1.2 seconds is a reasonable requirement for surface surveillance. Because of competing activity on the 1090-MHz link, surface ADS with an omnidirectional antenna can accommodate about 250 aircraft with this level of performance. By using sector antennas with a restricted field of view, the capacity for surface ADS can be increased to approximately 500 aircraft. The downlooking directional antennas prevent the surface system from picking up any airborne replies with the exception of low aircraft on final approach. Performance on the airport surface is more likely to be determined by site dependent factors of antenna placement, multipath, and resulting coverage.
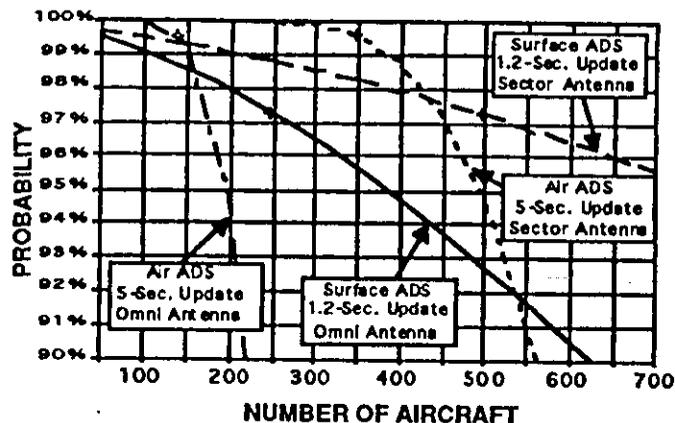

Figure 3. ADS Link Capacity.

The probability required to detect an airborne aircraft in a 5-second period is 99.5 percent. This was chosen to be comparable to the surveillance performance of modern SSRs like the Mode S sensor. From the above figure it can be seen that the small terminal area Omni Air ADS can handle up to 140 aircraft, but by using six antennas to restrict the field of view, the en route area Sector Air ADS can handle up to 350 aircraft. This is a reasonably high capacity given that these sensors will not be required in areas where aircraft densities are exceptionally high. It is expected that the large terminal areas will continue to be served by the Mode S sensors now in production.

DGNSS Uplink Performance

The uplink design shares the work done to support the DGNSS Instrument Approach System (DIAS) [2]. The power budget for the uplink was based on two simple modifications to the TCAS equipment: a 5-ft vertical aperture cylindrical antenna with 4 dBi gain and lower loss antenna cables. This gives an uplink power budget adequate to support the 20-nmi range required by the DIAS function (Table 3). This type of unit might also serve as a basic unit used for airport surveillance.

For air surveillance both the terminal area and en route systems have to support a greater range. Although only the receiver is needed to perform the ADS function, the ground units also support data link functions in the small terminal and en route areas. In order to match the receiver range, a 3-kW final amplifier is added to the transmitter. This, together with the antenna gain discussed earlier, provides uplink performance matched to the downlink.

The uplink is also subject to interference or garble from activity on the 1030-MHz frequency from other ground transmitters as well as TCAS interrogations. The 1030 MHz band has been measured in the past and been found to have less activity than is expected on the downlink. It is dominated largely by ATCRBS interrogations and suppression pulses. RTCA Task Force 2 conducted an extreme worst case analysis of the interference expected for the DGNSS uplink [10]. It showed that even with an extremely heavy load expected where there were eight airports located within 20 nmi,

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each with six runways, that the uplink channel was able to give very high delivery reliability with channel occupancy increased by only 0.35 percent.

Table 3. DGNSS UpLink Power Budget

System Parameter	DIAS Omni	Terminal Omni	Enroute Sector
Transmitter			
Power (dBm)	57	65	65
Cable Loss (dB)	-1	-2	-2
Antenna Gain (dBi)	4	4	8.5
Path Loss (dB) for:	-124.5	-132.5	-138.5
Range, nmi	20	50	100
Receiver			
Antenna Gain (dBi)	0	0	0
Cable Loss (dB)	-3	-3	-3
Power (dBm)	-67.5	-67.5	-69
Min Detect. (dBm)	-77	-77	-77
Link Margin (dB)	9.5	9.5	8

The airport surveillance uplink will broadcast DGNSS corrections to all aircraft. Although the DIAS requires that DGNSS corrections be delivered with an error probability of 6×10^{-8}, this same transmission protocol can be applied to deliver DGNSS corrections over the shorter ranges on the airport surface. There are two differences noted for airport surveillance: (1) the 15-second maximum period between corrections could be lengthened considerably; and (2) we assume that all transmitters on an airport will be synchronized so that they do not interfere with each other.

ADS EXPERIMENTAL PROGRAM

Earlier Experimental Programs

Mode S Experimental Facility (MODSEF)

Throughout the early development of Mode S, Lincoln Laboratory provided experimental support to verify that the concepts would work with real equipment. In the course of building the Mode S Experimental Facility (MODSEF), several sets of Mode S processors 8cre constructed which were used for testing Mode S. It is the existence of this equipment that made possible the rapid development of both the DGPS-Mode S Precision Approach and the ADS-Mode S system concepts.

DGPS-Mode S Precision Approach

Under the sponsorship of the FAA Satellite Program Office, Lincoln started an experimental program in October 1992 to demonstrate that Mode S could support DGPS Special Cat I. DGPS avionics and a reference station were obtained from Trimble Navigation. A Mode S Processor was repackaged and modified to support the omnidirectional transmission of DGPS corrections.

A Collins Mode S transponder was installed in a Cessna 172 aircraft along with a VME-based airborne processor, as part of the Mode S data link program. This equipment provided a data link interface through an ARINC 429 bus that was used to receive the DGPS corrections. Software was written to receive and assemble the uplinked DGPS corrections and format them for a Trimble TNL 2100 DGPS receiver.

The system was flight demonstrated for the FAA in April 1993, six months after the start of the program.

ADS Airborne Reporting Test

The Mode S production sensor at MODSEF had previously been used to test the Mode S data link to the Cessna 172. Once the Trimble TNL 2100 GPS receiver had been installed and interfaced to the existing Mode S data link equipment, it was possible to test the basic ADS capability. In February 1993, MODSEF was able to receive downlinked GPS position reports. The airborne processor received the GPS positions from the TNL 2100, reformatted them and placed them in one of the registers in the Collins transponder. MODSEF then interrogated the transponder and it downlinked the content of that register. Software was written to allow MODSEF to display the downlinked ADS reports along with the Mode S track reports.

This provided the first demonstration of ADS using the Mode S data link. It also provided the first comparison of the GPS absolute position reports with the relative tracking data output from the Mode S sensor.

Surface ADS Demo: Hanscom Field

The basic purpose of the Hanscom Field demonstration was to give an initial proof that the long ADS squitter concept works. It also provided an initial look at the problems of coverage, multipath, and link reliability.

Various hardware components were prepared for the Hanscom surface ADS demonstration (Figure 4). These included: a differential GPS ground reference station; two ADS-Mode S omnidirectional ground stations; a C-172 aircraft; a separate ground vehicle; recording systems; and a display system.
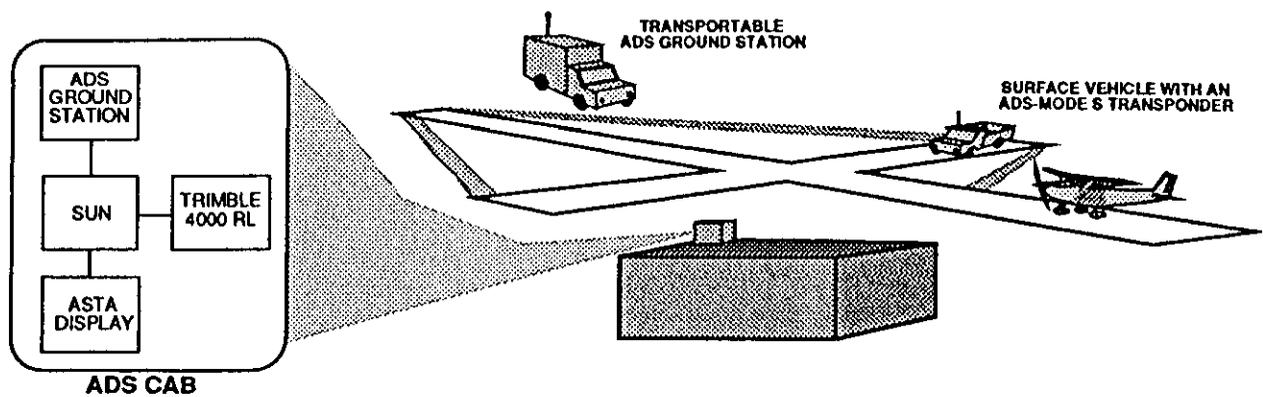
Figure 4. ADS Demonstration Equipment at Hanscom

Demonstration Equipment

One of the ADS-Mode S ground stations was located in a cab on top of a hangar at Hanscom Field. The other was initially set up on a tower some two miles from the field, and will soon be moved inside the Transportable ADS Ground Station (TAGS) van. The cab location provides good coverage of the runways and taxiways at Hanscom, plus it is high enough (75 ft above ground level) that it should provide good air surveillance coverage as well.

Preliminary Demonstration Results

The system performance was tested by taxiing the C-172 around a loop that encompassed the periphery of the field and all the main taxiways, only the active runways were excluded to avoid affecting operations at the field. The long squitter was evaluated by plotting the percentage of ADS squitters received for a ±25-second period every 50 m on a map of Hanscom Field (Figure 5). This showed areas where the squitters were received 100 percent of the time and other areas where some of the squitters were missed by a single ground station located in the ADS Cab. The raw, half-second squitter reception probability was 92 percent averaged over the path shown in Figure 5. Integrating over the 1.2-second window assumed in the analysis, the detection probability is 98 percent which is very good for a single receiving station. Subsequent tests with two receiving stations gave a joint detection probability of greater than 99 percent.

One of three factors could cause a squitter to be missed: loss of line of sight, shadowing of the aircraft antenna by other parts of the aircraft, and multipath induced self interference. Visibility is good except for blockage by the Hanscom control tower (i.e., ≤1 percent). Shadowing by the aircraft may be a factor in one of the areas. Multipath from hangars has

been identified as a problem in testing done previously at Logan Airport [9]. There are hangars directly behind the aircraft in two of the problem areas at Hanscom which could produce multipath interference by causing a replica delayed 1/4 to 1 µs. It is likely that as the aircraft moves it goes through interference zones that cause between 10 and 20 percent of the squitters to be unreadable (each has a 24-bit cyclic redundancy parity code). The TAGS van will be located to enhance coverage in areas where the ADS Cab experiences problems.

The ADS surface surveillance requirement is to unambiguously locate an aircraft on movement areas and to discriminate it from other vehicles, which implies an accuracy requirement of about 5 to 10 meters. The DGPS accuracy of 2 to 5 meters is more than adequate for that purpose. Actually, the detection of movement on the surface is equally important in avoiding runway incursions. This is the reason for the movement field in the ADS message.

While metric measurement of accuracy was not explicitly carried out in the Hanscom field demonstrations, we noted several things about the accuracy of the DGPS position: (1) when the aircraft was taxiing down the center of the taxiway the display showed it on the taxiway centerline (Figure 5) so the lateral error was always less than 2 meters; (2) even when there was a loss of DGPS corrections for periods up to the 30 seconds, the position of the aircraft was not noticeably degraded by using old corrections. Based on this experience, older (e.g., 40-60 seconds) updates may continue to be used if newer updates are not received. This seems reasonable since the accuracy needed for surface ADS is not as great as that for precision approach. More precise measurements of positional accuracy will be made in the coming months.
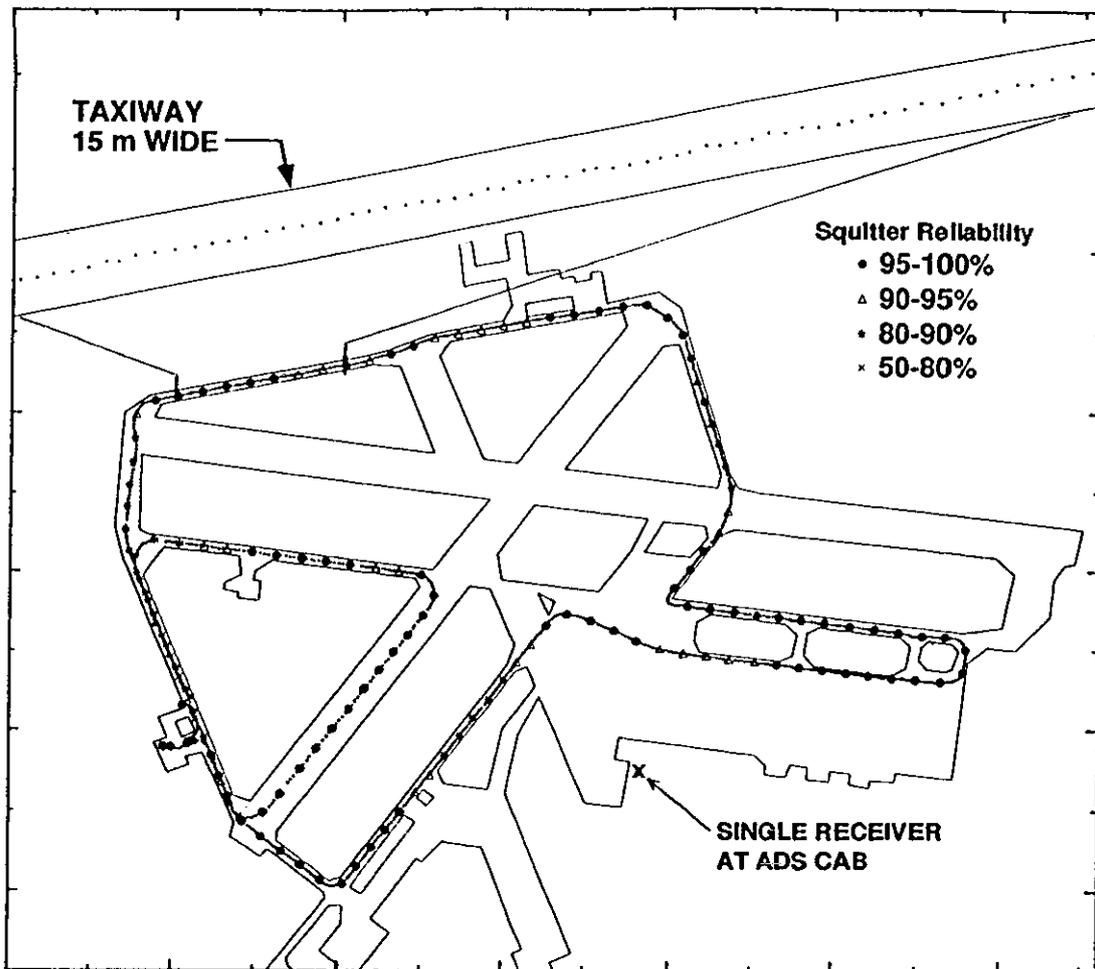
Figure 5. Long Squitter Test Results

It is important to note that the ADS display used standard ATC track symbology overlaid on the Hanscom field map. This showed aircraft ID, heading (also depicted as a directional arrow), and velocity in knots. During the testing, both the C-172 aircraft and the squitter test vehicle were displayed simultaneously.

The performance of the uplink was measured by recording on the aircraft the time between successful uplinking of a complete set of DGPS corrections. (Note: if this time was not less than approximately 30 seconds, the DGPS receiver would automatically revert to uncorrected GPS operation, which usually caused a jump in reported position.) In the loop around Hanscom (shown above) two identical sets of updates were broadcast every 2 seconds. There were only two times that the uplink corrections were not updated within 15 seconds, and in both these cases, the update was received in time for the DGPS receiver to stay in differential mode.

Surface ADS Demo: Logan Airport

An operational suitability assessment of the ADS-Mode S squitter for surface surveillance is scheduled for Logan Airport, Boston, in February 1994 (Figure 6). Four industry-supplied ground stations will be positioned around the periphery of the airport to receive long squitters from the aircraft and ground vehicle equipped with modified transponders. The industry supplied ground stations are modified TCAS units.

Data from the four stations are integrated by a Sun processor and displayed along with tracks from a Lincoln Laboratory experimental primary radar (ASDE-X) being tested at Logan Airport for surface detection. These tests will measure the performance of the ADS-Mode S system in a complex airport environment. Coverage, link reliability, and multipath problems will receive special attention. Output of the tests will allow an assessment of the number of ground stations needed to reliably cover a large airport complex as well as how to avoid problems with signal propagation.
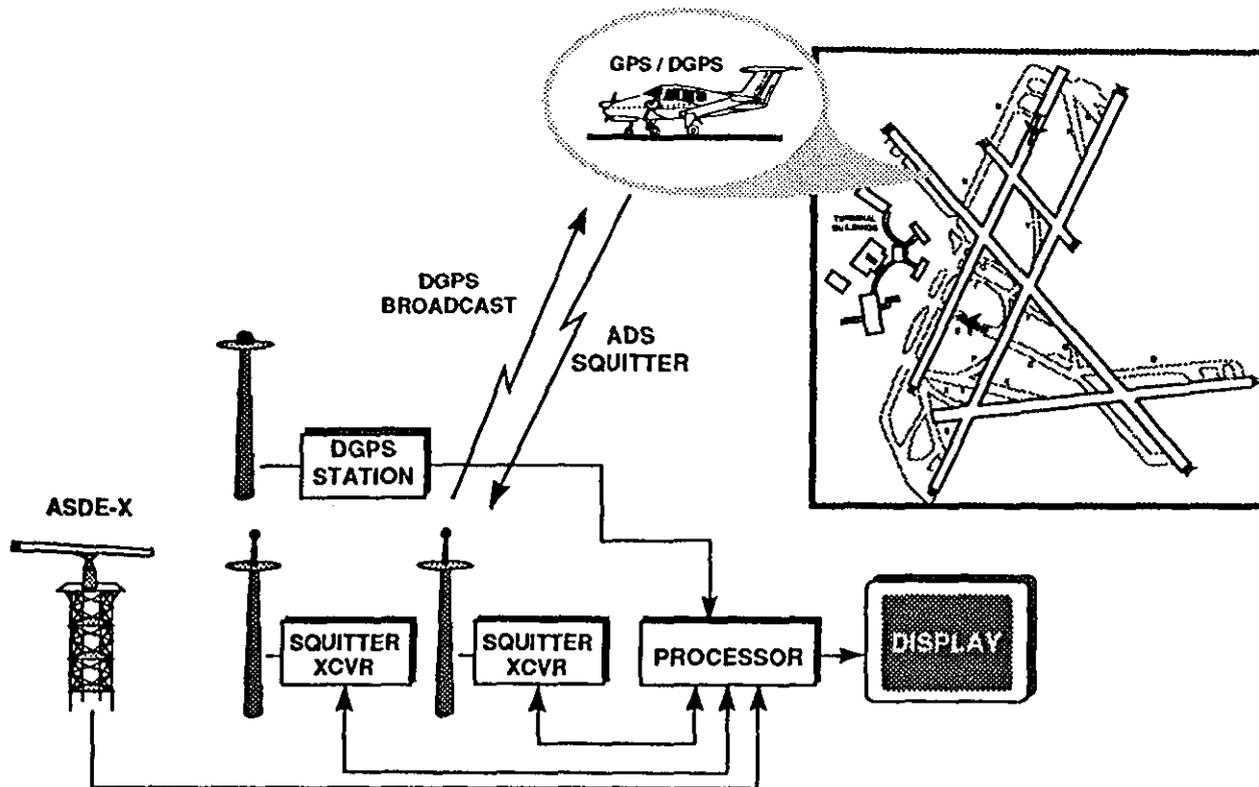
10

Figure 6. Planned ADS Demonstration at Logan.

STANDARDS

Standards are an important part of any avionics system that hopes to achieve widespread use. Over the last year, the RTCA Special Committee 159 has had a number of working groups developing documentation for new GNSS standards. Recently work was completed on the DGNSS Instrument Approach System: SCAT-I MASPS [6]. Appendices A and G of this standard describe the implementation of the DGNSS uplink using the Mode S omnidirectional data link. Future work of the committee will encompass GNSS-based airport surveillance as well as sole means navigation standards. Recently, the AEEC has proposed a differential GNSS supplement to ARINC Characteristic 743A, "GNSS Sensor" which defines the interfaces required for differential inputs.

Standards for Mode S equipment have an even longer history. While the Mode S sensor was in development, the avionics were being standardized and produced. The transponder was standardized (RTCA/DO-181A) and then produced in significant quantities. The collision avoidance system (TCAS) was then standardized (RTCA/DO-185) and designed to use these transponders and the Mode S frequencies and protocols. TCAS and Mode S transponders have now been installed on almost all US commercial aircraft with more than 30 seats.

International acceptance and support for these standards now plays an even larger part in the global market place. ICAO has been developing standards [5] and leading the way toward widespread international acceptance of Mode S. These standards include the use of Mode S for the ATN as well as special real-time and broadcast functions not part of ATN. The RTCA Task Force 2 on Data Link has recently favored the use of Mode S for the local DGNSS data link.

The Mode S Transponder standard (DO-181A) will require minor additions to cover the operation of the long squitter. ARINC Characteristic 743A will require additions to describe the interface from the Mode S data link for inputting the DGNSS corrections. TCAS standards (DO-185) will require modification once the use of ADS for collision avoidance is worked out.

SUMMARY

By combining the GNSS Navigation System with the Mode S Communication and Surveillance System there are a number of potential benefits to air traffic control—foremost, may be Automatic Dependent Surveillance. In the ADS-Mode S concept, aircraft determine their position using GNSS and transmit that information via a Mode S transponder. These transmissions would be received by FAA ground-based receivers for air traffic control purposes and by other aircraft for CDTI (cockpit display of traffic information).

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The aircraft transponders would automatically broadcast the position reports twice a second at the 1090-MHz beacon frequency using a spontaneous message known as a squitter. The system design, operational concept, equipment necessary to conduct the tests and demonstrations, and results from the first tests were presented.

The proof-of-concept demonstration of the ADS-Mode S concept has just been completed at Hanscom Field in Bedford, Massachusetts. These tests evaluated the applicability of ADS-Mode S for surface surveillance. The objectives of the experiments were to (a) establish the feasibility of broadcasting long (i.e., 112 bit) squitter messages containing the GNSS position, (b) examine GNSS multipath and siting problems for DGNSS reference stations, and (c) measure the coverage and link reliability of the ADS ground stations. The proof-of-concept demonstration will soon be followed by additional testing aimed at quantifying the benefit of ground station site diversity, and will include some air surveillance testing.

Results showed that use of GPS for automatically reporting aircraft position is feasible using the Mode S communication and surveillance system.

ACKNOWLEDGMENTS

APPENDIX: COMPACT ADS REPORTS

Each squitter message must be coded to fit within the 56 bits available in the 112-bit long squitter message. This appendix describes how each message is coded. The message type field is 4 bits long and includes a position figure of merit based on whether the GPS position is corrected either locally or by a wide area differential correction. The message formats described here are experimental and subject to change in future tests.

Table A-1. Message Types and Figure of Merit

TYPE (FOM)	MESSAGE	FIGURE OF MERIT
1	Aircraft ID	
	Airborne Position:	
2	DGPS	5 m
3	WADGPS	10 m
4	GPS	100 m
	Surface Position:	
5	DGPS	5 m
6	WADGPS	10 m
7	GPS	100 m

Each of the three general message types are described below.

Aircraft ID Message

The standard ICAO aircraft identification will be squittered every 5 seconds in order to identify the aircraft both to ground surveillance as well as airborne CDTI users. For general aviation, this will contain the tail number, for commercial flights it will contain the flight number. Each character is coded as a 6-bit alpha-numeric using the lower 6 bits of ISO Alphabet #5.

Table A-2. Aircraft ID Message

BITS	FIELD	RANGE
4	Type	Equal 1
4	Not Used	TBD
	Aircraft ID	
48	8 6-bit Characters	A/N

Airborne Position Message

Each second the position report from the GPS receiver is encoded and placed into the Mode S transponder register. The position is either received on the UTC second or can be extrapolated to the next UTC second. One bit is included in the message to indicate if this is an even or odd UTC second. The transponder will squitter this message every half second so the latency in the link is only a few hundred milliseconds. Of course the ground station must restore the rest of the UTC time field upon reception.

Table A-3. Airborne Position Message

BITS	FIELD	LSB	RANGE
4	Type (FOM)		Table
1	Turn Indicator		1=Turn
5	Spare		TBD
11	Altitude (baro)	25 ft	-1 to 50 kft
1	Time (UTC),	1 s	0=Even
17	Latitude	5.1 m	0 — 6°
17	Longitude	≈ 5.1m	0 — ≥ 6°

Altitude is received from the barometric altimeter and coded using the lower 11 bits of the standard barometric aviation altimeter. Aircraft above 50 kft are handled by a separate high altitude format.

The latitude and longitude are received from the GPS receiver in the usual degree and decimal minute format. A special encoding algorithm has been developed that encodes it into a 17-bit integer. This algorithm provides for seamless encoding and decoding that gives uniform precision worldwide and is unambiguous for a minimum range of 360 nmi. The 360-nmi ambiguity is removed by the algorithm after two successive reports. The 360-nmi minimum range was chosen to insure that aircraft at or below the service ceiling of 43 kft would be beyond the radar horizon for a ground sensor with a 100-nmi range.

A 1-bit turn indicator is derived from onboard measurements and is transmitted as an aid to trackers.

Surface Position Message

The surface position message is similar to the airborne message except that the altitude is replaced by a movement and heading field. The heading is encoded from the GPS velocity, that is when it was last greater than 0.5 kts. Alternatively, the heading may be available from a directional gyro if the aircraft is so equipped.

Table A-4. Surface Position Message

BITS	FIELD	LSB	RANGE
4	Type (FOM)		Table
3	Spare		TBD
6	Movement		Table
8	Heading	1.4°	0 — 360°
1	Time (UTC)	1 s	0=Even
17	Latitude	0.64 m	0 — 0.75°
17	Longitude	≈ 0.64m	0 — ≥ 0.75°

The movement field is encoded from the GPS velocity according to this table:

Table A-5. Meaning of 6-bit Movement Field

CODE	MOVEMENT TABLE	VALUE
0	Not Moving	< 0.5 kts
63	Backing —Ramp Movement	< -0.5 kts
62	Acceleration—Take-Off	TBD
61	Deceleration—Braking	TBD
1 - 59	Velocity —Constant	1 to 59 kts
60	Velocity—Constant	> 60 kts

The latitude and longitude are encoded with greater precision than the airborne message and need be unambiguous at a shorter range (i.e., 45 nmi).

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