ADS-MODE S*

by

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INTRODUCTION

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). A cornerstone of the FANS is an increasing reliance on satellite-based position-determining systems such as the Global Positioning System (GPS). In the case of surveillance, aircraft position information is automatically downlinked to ground controllers. This technique is known as Automatic Dependent Surveillance (ADS).

ADS-Mode S is an ADS system concept utilizing the frequencies and formats of the Mode S system for downlinking position information and also uplinking differential GPS (DGPS) corrections. The result is an integrated concept for surveillance that permits aircraft equipped with a Mode S transponder and a GPS receiver to participate in both ADS and beacon ground environments. This makes possible a smooth transition of the National Airspace System (NAS) secondary surveillance system from a beacon-based to an ADS-based environment. In addition, several other benefits from ADS-Mode S accrue to the Traffic Alert and Collision Avoidance System (TCAS) and to the Mode S Data Link system. [1]

SYSTEM CONCEPT

In the current Mode S design, each Mode S transponder randomly radiates (squitters) its unique Mode S address in an azimuth-omni-directional patttern once per second. This squitter is a 56-bit transmission of about 60 μs duration, broadcast on the Mode S transponder reply frequency (1090 MHz).

Figure 1 illustrates the current Mode S squitter. The squitter is used by TCAS to detect the presence of Mode S-equipped aircraft. In operation, TCAS listens for squitters, extracts the 24-bit Mode S address contained in the squitter data and uses this address as the basis for discrete interrogation, as required, to perform surveillance on Mode S-equipped aircraft.

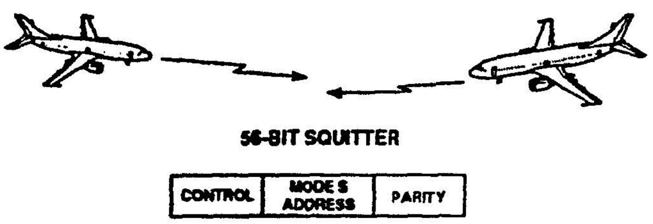

Figure 1. Current Mode S squitter for TCAS acquisition.

Note that the squitter is in operational use with TCAS. Its performance is well understood from the design and validation of TCAS as well as the substantial experience with TCAS as an operational system.

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Since the Mode S message protocol defines both 56-bit and 112-bit replies, the proposed ADS-Mode S approach is to define an additional squitter that uses a 112-bit format (a long squitter) as shown in Figure 2. This creates a 56-bit message field for ADS data. All other fields remain the same as in the original short squitter.

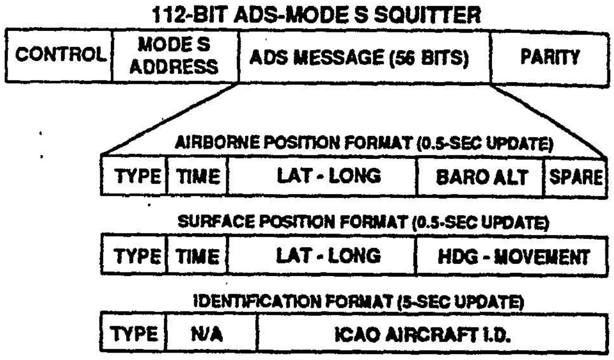

Figure 2. ADS-Mode S Squitter Formats.

There are three types of long squitters, one for air surveillance, one for surface surveillance, and one for flight identification. An aircraft squitters either the first or the second once every 0.5 seconds, and squitters the latter once every 5 seconds.

In operation, aircraft equipped with a Mode S transponder and a GPS receiver determine their position once every second. This position information is inserted into the 56-bit ADS message field of the long squitter and broadcast twice every second to increase the probability of a successful reception. The current 56-bit short squitter continues to be broadcast once per second for compatibility with TCAS.

Simple omni-directional or sector-beam ground stations receive the long squitter to provide for ground-to-air surveillance, as illustrated in Figure 3. TCAS aircraft could also eventually be made to receive the long squitter to support acquisition of Mode S aircraft, as with the current short squitter.

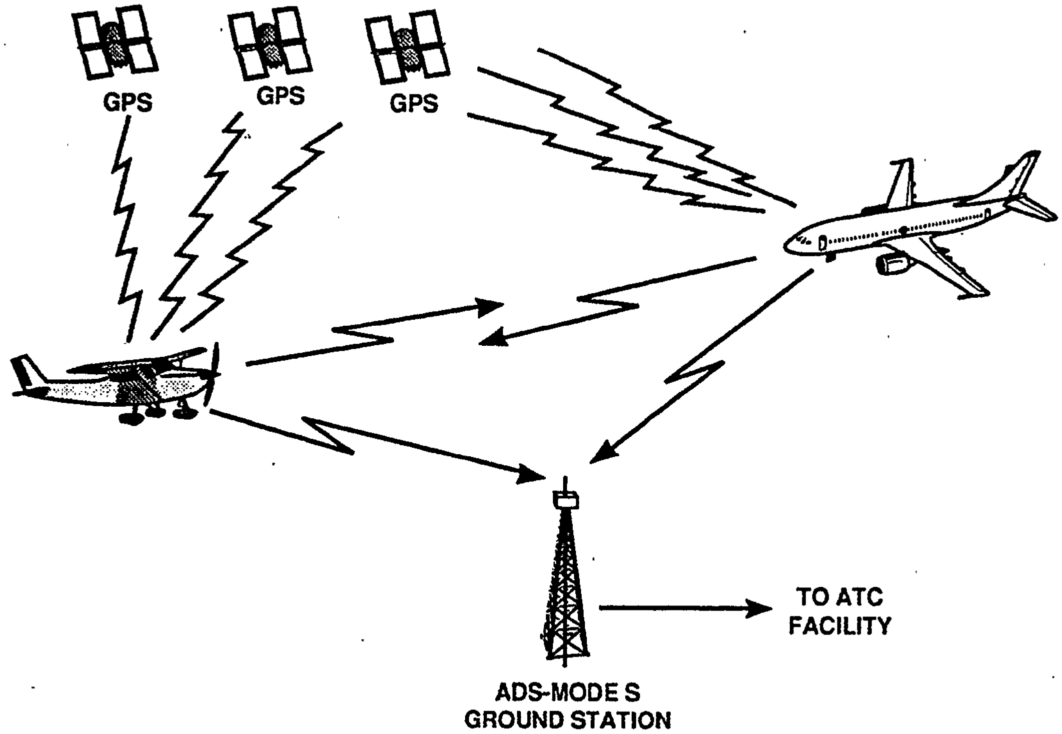

Figure 3. ADS-Mode S Concept.

SURVEILLANCE APPLICATIONS

The most important surveillance applications of ADS-Mode S are

- Surface, for runways and taxiways[1]
- Air-Ground
  - En route
  - Terminal
  - Precision Runway Monitoring (PRM)[1]
- Air-Air
  - Improved TCAS
  - Cockpit Display of Traffic Information (CDTI).

Airport surface surveillance is illustrated in Figure 4. Aircraft squitter their DGPS-derived positions while operating on runways and taxiways. These squitters are received by several receiving stations around the periphery of the airport. Two such stations are shown in the figure, but the actual number for each airport will be determined by squitter reception performance in the multipath environment of the airport surface. Additional measurements are being made on airport surfaces in order to better estimate this performance.

Air surveillance for both a terminal area and en route is shown in Figure 5. Aircraft determine their position using GPS and broadcast this position via the ADS-Mode S squitter. The squitter is received by terminal and en route ground stations. The terminal antenna is shown as a single omni, which is estimated to be capable of a squitter reception range of 50 nmi with a low-noise front end. Uplink transmit range is also 50 nmi with a 3 kW transmitter.

For en route operation, a 6-sector high-gain antenna (with six independent low-noise receivers and one 3 kW transmitter) is used in order to obtain a 100 nmi downlink and uplink range. The 6-sector antenna may also be used in high-traffic-density areas in order to limit the number of aircraft being processed by any one receiver.

Both terminal and en route configurations provide Mode S data link service. In addition, terminal stations provide uplink DGPS corrections for PRM and for GPS-based category 1 precision approach. The latter application is currently being defined by RTCA Task Force 2.

The Mode S data link capability provided by ADS ground stations will supplement and enhance that provided by the 133 Mode S sensors currently beng procured for the busiest terminal and en route secondary surveillance radar (SSR) sites.

TCAS USE OF ADS-MODE S DATA

The availability of position data in the ADS-Mode S squitter also makes it possible to significantly improve the operation of TCAS.

For security reasons, the Air Force intentionally perturbs the accuracy of GPS through a technique called "Selective Availability" or SA. Analysis of TCAS operation indicates that ADS-Mode S will be able to support passive surveillance of Mode S aircraft to a Tau of 40 seconds if SA is turned on (as it is today). Tau in TCAS terms is the time to closest approach. Operational experience indicates that an intruder with a Tau of about 40 seconds is observed on an average of once per hour per TCAS. Thus, ADS-Mode S will permit TCAS to perform most of its surveillance passively.

If SA is turned off, TCAS will be able to perform all of its surveillance of Mode S aircraft passively. The only time that TCAS will be required to transmit is when it is performing coordination for an avoidance maneuver. Experience indicates that this occurs only once every 45 hours per TCAS.

In addition to surveillance benefits, the use of the ADS position information can reduce the alert rate for TCAS II through the use of miss distance filtering. ADS-Mode S also provides the basis for TCAS III, the version of TCAS that uses horizontal avoidance maneuvers. The use of ADS position information from intruder aircraft appears to provide a more achievable basis for TCAS III than the alternative of precision antennas to measure bearing angles.

[1] These applications require the 3 to 5 m position accuracy of local-area DGPS.

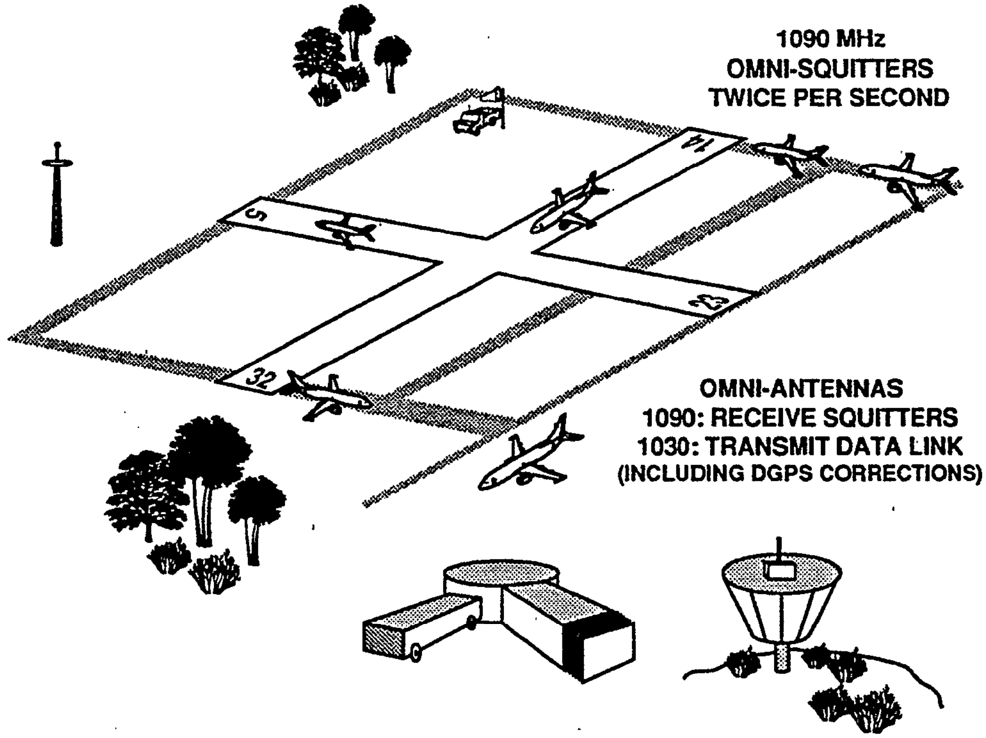

Figure 4. ADS-Mode S Surface Surveillance.

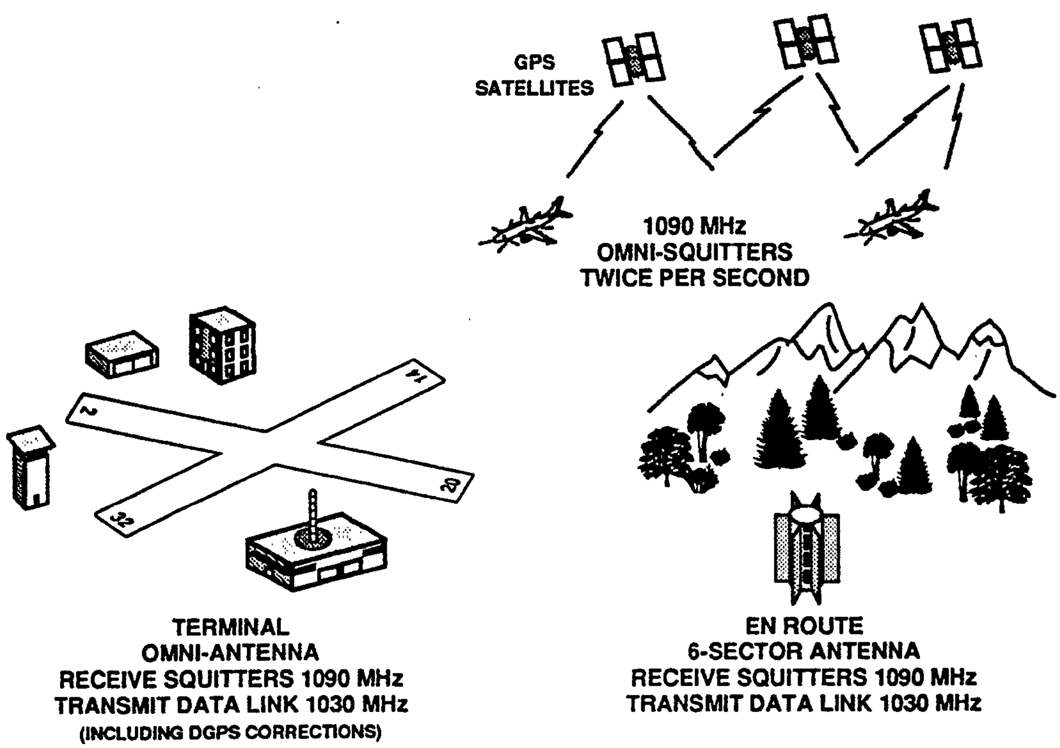

Figure 5. ADS-Mode S Air Surveillance.

CDTI VIA ADS-MODE S

CDTI is *feasible* for aircraft which are equipped with a 1090 MHz receiver. Such aircraft would listen to long squitters from nearby aircraft and display their positions on a small cockpit display. A range of 14 nmi can be supported for CDTI using receivers equivalent to those in TCAS. In low interference environments this range can be extended to 40 nmi through the addition of a low-noise front end to the receivers. TCAS aircraft already have 1090 MHz receivers, which would require small modifications, but other aircraft would have to equip in order to realize this benefit.

OTHER SURVEILLANCE APPLICATIONS

ADS-Mode S is also a low-cost means for surveillance (1) for small terminals which do not qualify for high-cost ground beacon equipment, and (2) for en route gap filling in mountainous or remote areas. TCAS II units sell for about $100K, and a simple omni ADS ground station which is a modified TCAS unit is expected to be comparably priced.

DATA LINK APPLICATION

An important navigation benefit from ADS-Mode S is the ability to execute category 1 precision approach, using DGPS corrections via uplink messages from an ADS ground station. Category 1 precision approaches would be possible at every airport which has an ADS-Mode S ground station, for all aircraft equipped with a GPS receiver and Mode S transponder capable of receiving uplink messages (a level 2 or higher transponder).

It is intended that ADS ground stations be capable of two-way Mode S data link, which could provide graphical weather service and similar services to all types of aircraft. This would supplement the data link capability of the 133 Mode S radars and extend data link coverage down to a much lower altitude almost everywhere in CONUS. Aircraft equipped with a Mode S transponder capable of two-way data link would be able to benefit from the extended data link capability of ADS-Mode S.

CRITICAL ISSUES

An intensive development program for the ADS-Mode S concept was begun at Lincoln Laboratory in December 1992. The initial focus of the program is a critical issues study, system design, and the surface surveillance application.

One of the critical issues under study is 1090 MHz channel capacity and interference. Table 1 shows a worst-case reply rate scenario for a single Mode S transponder on a per second basis.

Table 1. SQUITTER IMPACT ON 1090 MHZ CHANNEL CAPACITY

CHANNEL OCCUPANCY FROM ONE TRANSPONDER DURING ONE SECOND		
	MESSAGES	OCCUPANCY (μ SEC)
ATCRBS		
GROUND	100	2000
MODE S		
GROUND	1 SHORT	64
	4 LONG	480
SQUITTER	1 SHORT	64
ALL-CALL	1 SHORT	64
TCAS	5 SHORT	320
TOTAL WITH CURRENT SQUITTER		2992 μSEC 0.299%
ADS SQUITTERS	2.2 LONG	264
TOTAL WITH ADS SQUITTERS		3256 μSEC 0.326%

Ground stations are assumed to interrogate the transponder at a total aggregate rate of 100 Air Traffic Control Radar Beacon System (ATCRBS) interrogations per second, leading to a reply channel occupancy of 2000 microseconds per second. Mode S activity adds an additional 992 microseconds as shown. For ADS-Mode S, the addition of two 112-bit squitters per second adds 240 microseconds to the channel occupancy. Also, the additional squitter for ID once per 5 seconds adds an average of 24 microseconds per second. The total increase in squitter occupancy of 264 microseconds per second thus increases the total channel occupancy for a transponder from 0.299% to 0.326%. This is considered to be a tolerable increase.

Since the use of the ADS-Mode S squitter will make it possible for TCAS and ATC surveillance systems to operate in a passive mode, it is equally appropriate to conclude that the use of the longer squitter has the effect of <u>reducing</u> the occupancy of the reply channel.

In order to estimate the aircraft operating density for ADS-Mode S air surveillance, an analysis was conducted which required that the probability of an update at least once every 5 seconds should be greater than or equal to 99.5%. This performance is representative of the current surveillance system. Results of the analysis are shown in Table 2.

Table 2. Maximum Number of Aircraft Which Can Be Handled by an ADS Ground Station for Various Levels of ATCRBS Replies

ADS/MODE S AIRCRAFT OPERATING DENSITY 5-SECOND UPDATE, 99.5% RECEPTION PROBABILITY				
	REPLIES/ AIRCRAFT/SEC		MAXIMUM AIRCRAFT IN RADIUS R	
CASE	ATCRBS	MODE S	OMNI ANTENNA R=150 nmi	6-SECTOR ANTENNA R=250 nmi
1 *	120	14	85	215
2	60	14	140	350
3 **	0	14	280	700

* CURRENT HIGH DENSITY ATCRBS ENVIRONMENT

** FUTURE ALL MODE S WITH NOMINAL DATA LINK ACTIVITY

Case 1 is the worst case ATCRBS interference scenario used earlier, except that an additional load of 20 ATCRBS replies per second has been added for TCAS operation, and the number of Mode S replies per second has been increased to 14 to account for the ADS squitters. Note that this is an extreme worst case since it represents the highest ATCRBS transponder reply rates observed in the development of Mode S and TCAS, and includes an anticipated worst case for Mode S. Also, approximately 75% of the ATCRBS replies elicited from the ground are due to military interrogators. This component of the interference scenario is expected to decrease as military activity is reduced.

Another worst case assumption is that every reply generated is received at a signal strength high enough to perturb the detection of the desired squitter. The Mode S reply uses pulse position modulation and is robust to interfering signals that are lower in power than the desired signal. Therefore, interference caused by replies from distant aircraft would be unlikely to interfere with the reception of a squitter from a nearby aircraft.

Even with these worst-case assumptions, ADS-Mode S provides operation for the moderate numbers of aircraft shown in the table. Numbers are given within a radius of 150 nmi or 250 nmi for the omni and 6-sector case, respectively, because these are the maximum ranges from which interfering replies can be received. Operation for these numbers of aircraft is adequate for the majority of SSR sites not being provided with a Mode S radar.

Case 2 is more representative of what would be observed at all but the highest density sites. The resulting operational aircraft density is appropriate for nearly all SSR sites. Case 3 indicates the performance that would be achieved in an environment where ATCRBS interrogators have been eliminated. The numbers of aircraft which can be accomodated is satisfactory for the highest traffic density environments anticipated.

EXPERIMENTAL ACTIVITIES

Figure 6 is a sketch of a squitter proof-of-concept evaluation which was run at Hanscom Field, Bedford, MA, in July 1993. Three vehicles were equipped with long-squitter transponders — a C-172 aircraft, a C-421 aircraft, and a small ground vehicle. Two ground stations received the squitters, and a Sun workstation integrated the data which were then displayed on an appropriate background map. The primary objective of this work was to prove ADS-Mode S for surface surveillance, but some measure of air surveillance out to ranges of 50 nmi was performed as well. [2]

An operational suitability assessment of the ADS-Mode S squitter for surface surveillance in CONUS, and elsewhere, is scheduled for Logan International Airport, Boston, in February 1994. Figure 7 is a sketch of this operation. Four industry-supplied ground stations will be positioned around the periphery of the airport to receive long squitters from the 3 equipped vehicles mentioned above. The ground stations are modified TCAS units, which are simple and inexpensive.

Data from the 4 stations are integrated by a Sun processor and displayed, along with tracks from a Lincoln Laboratory primary experimental radar, named ASDE-X. ASDE-X is a low-cost Raytheon marine radar, modified by Lincoln Laboratory, and being tested at Logan Airport for a surface surveillance application. No effort is planned at this time to integrate ADS data with ASDE-X data.

Some early measurements of the ability of a single ground station to cover taxiways and runways at Logan International Airport is shown in Figure 8. The X labeled AMF is the location of the Lincoln Laboratory Airborne Measurements Facility which was used as an expedient simulation of an ADS ground station to receive existing short squitters from a Bonanza aircraft. The gray dots are locations from which the squitter was correctly received. Black dots are locations from which the squitter was not correctly received; most of these locations, above and below the terminal area, did not have line-of-sight to the AMF. The areas which have no dots are locations which were not tested, but which are presumably locations from which the squitter would be correctly rreceived because there is line-of-sight from the AMF site and no apparent multipath from structures. Notice the excellent coverage from one ground station, implying that 3 or 4 stations would provide nearly 100% coverage.

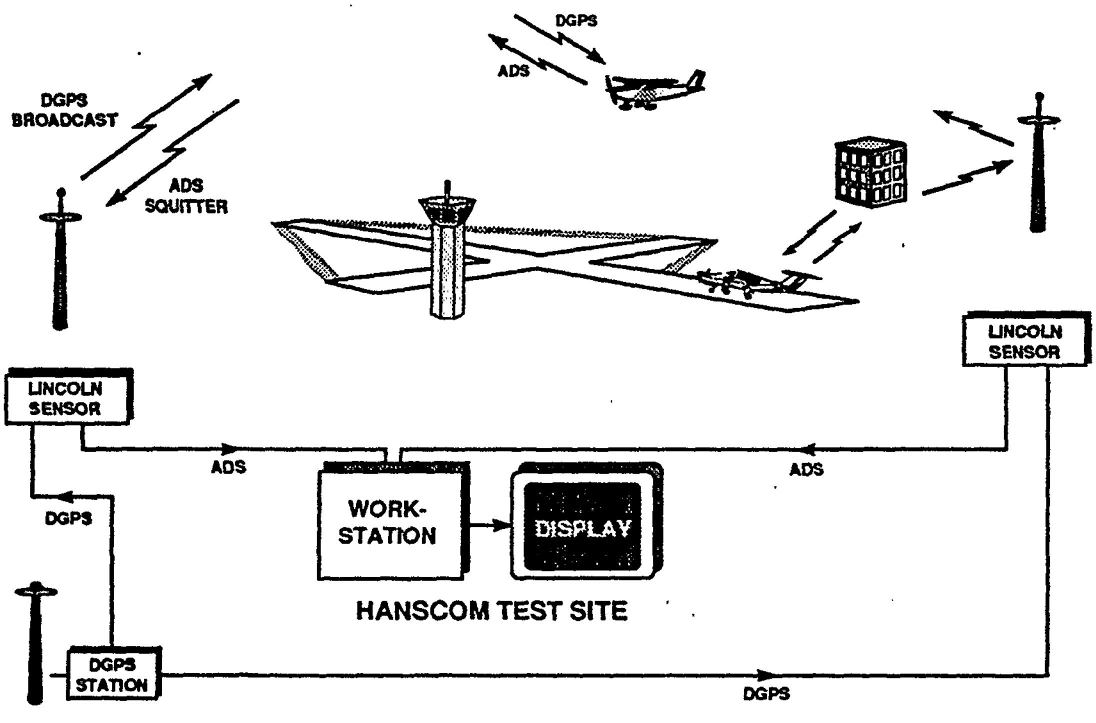

Figure 6. Squitter Proof of Concept Evaluation.

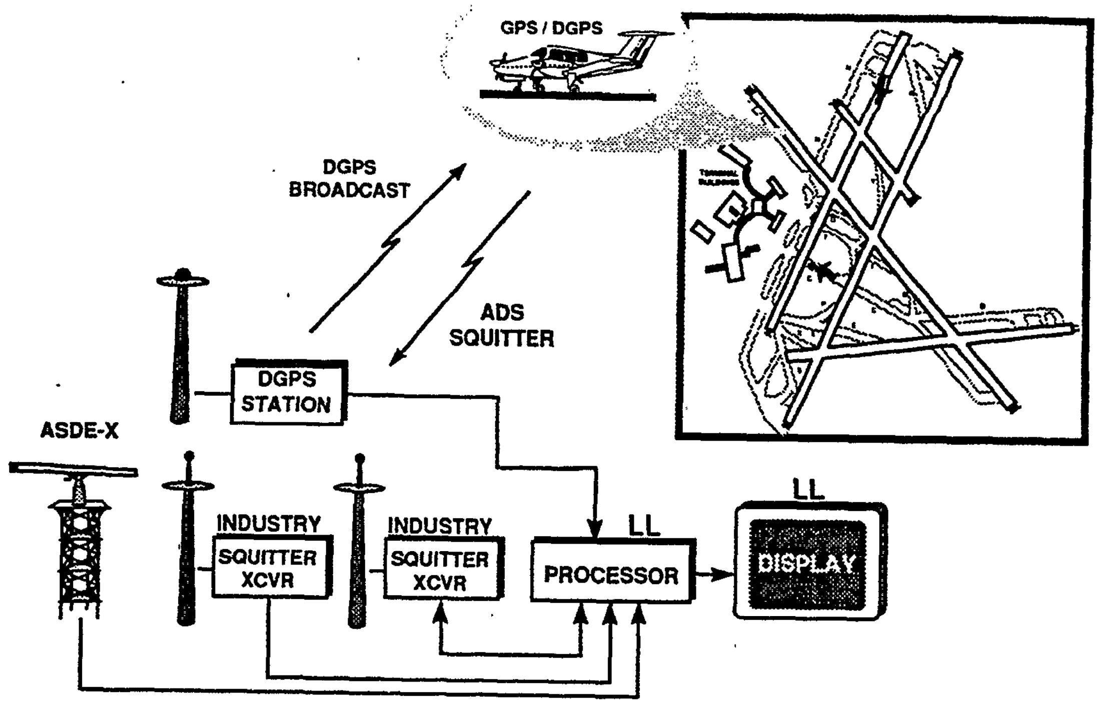

Figure 7. ADS-Mode S Operational Suitability Assessment, planned for Logan Airport in February 1994.

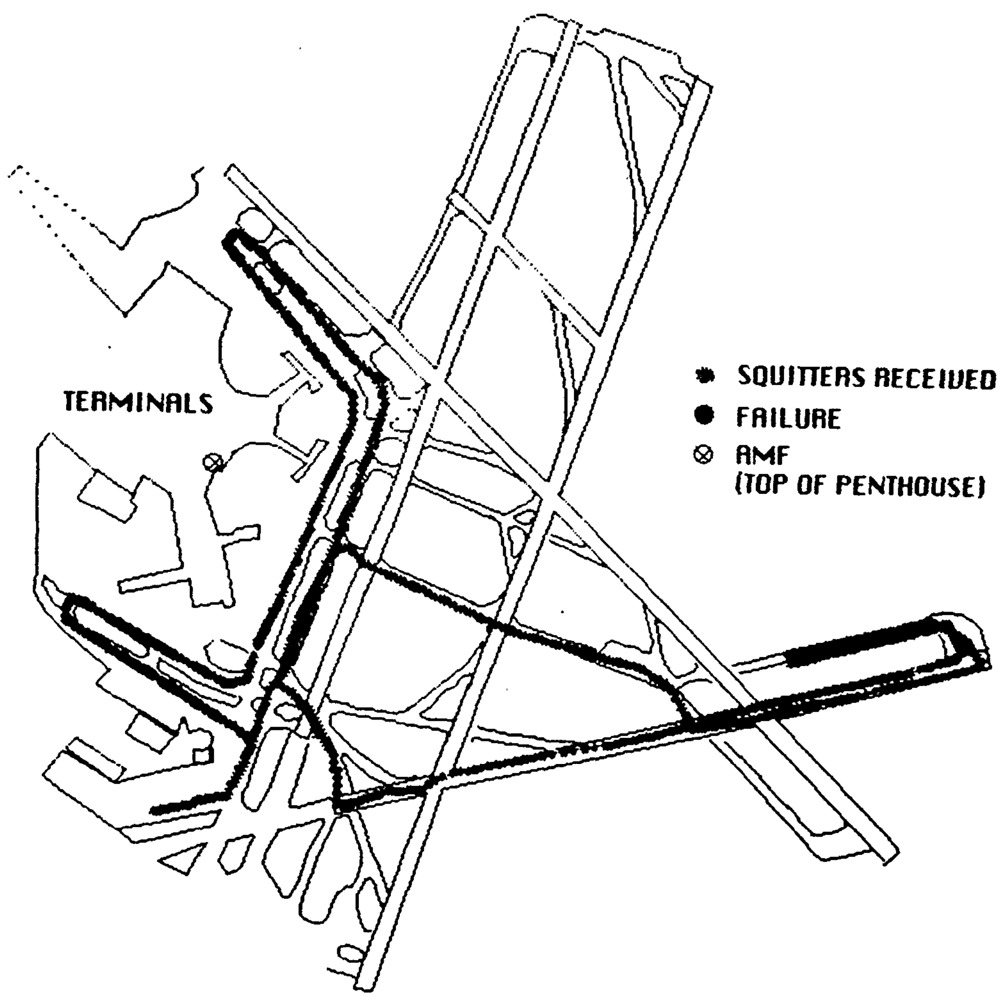

Figure 8. Preliminary Measurements of Logan Airport Coverage from One Ground Station Site (AMF).

SUMMARY

ADS-Mode S is an idea whose time has come, and it will provide significant benefits to the National Airspace System.

- It is a systems approach which supports ADS, enhances existing beacon surveillance applications, and also provides new surveillance, data link, and navigation capabilities.
- Since Mode S is an internationally accepted operational system on the beacon frequencies, there are no spectrum allocation problems.
- The system will be owned and operated by the FAA.
- It builds on the Mode S air and ground equipage now underway and requires only minor modification of existing Mode S transponders. A single Mode S transponder provides both ADS and beacon radar capability. This assures compatibility with existing beacon installations as well as operation in regions using ADS as the surveillance technique. This interoperability permits a smooth transition to ADS and is unique to ADS-Mode S among the techniques that have been proposed to implement ADS.

ACKNOWLEDGMENTS

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REFERENCES

[1] V.A. Orlando, "ADS-Mode S: Initial System Description," Project Report ATC-200, MIT Lincoln Laboratory, 2 April 1993.

[2] E.T. Bayliss, R.E. Boisvert, and G.H. Knittel, "Demonstration of GPS Automatic Dependent Surveillance of Aircraft Using Spontaneous Mode S Beacon Reports," MIT Lincoln Laboratory, accepted for the Proceedings of ION GPS-93, September 1993.