ADS-MODE S SYSTEM OVERVIEW*

Robert E. Boisvert, Vincent A. Orlando

MIT Lincoln Laboratory, Lexington, Massachusetts

ABSTRACT

ADS-Mode S is a system concept that merges the capabilities of Automatic Dependent Surveillance and the Mode S beacon radar. The result is an integrated system for seamless surveillance and data link that permits equipped aircraft to participate in ADS or beacon ground environments. This offers many possibilities for transitioning from a beacon to an ADS based surveillance system.

The ADS-Mode S concept is based on the use of the Mode S squitter. The current Mode S squitter is a spontaneous, periodic (once per second) 56-bit broadcast message containing the Mode S 24-bit address. This broadcast is provided by all Mode S transponders and is used by the Traffic Alert and Collision Avoidance System (TCAS) to acquire nearby Mode S equipped aircraft. For ADS-Mode S use, this squitter broadcast would be extended to 112 bits to provide for the transmission of a 56-bit ADS message field. The ADS squitter would be transmitted in addition to the current TCAS squitter in order to maintain compatibility with current TCAS equipment during transition.

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 the increasing reliance on the use of satellite-based navigation systems such as the Global Positioning System (GPS). A second thrust of FANS is surveillance based on the down linking of aircraft-derived satellite position information. This technique is known as Automatic Dependent Surveillance (ADS).

The general application of ADS will require that all aircraft in a region of airspace be equipped with satellite navigation and some form of data link. Since such general equipage will take many years, early implementation is expected to take place in regions where other surveillance techniques are not practical, e.g., in oceanic areas. Planning and limited testing are currently underway for ADS to support Air Traffic Control (ATC) management of oceanic routes (Ref. 1). Significant economic benefits are anticipated due to the reduction in separation (and the resultant capacity increase) made possible by ADS. This form of ADS connects an aircraft via a point-to-point link with the controlling oceanic ATC facility.

A more general form of ADS utilizing a broadcast mode is preferred in other areas. An ADS broadcast allows for one ADS transmission to simultaneously serve the surveillance needs of multiple ground ATC and airborne collision avoidance activities.

ADS-Mode S is a system concept that utilizes a broadcast mode to down link the ADS messages. It provides a natural transition from a beacon-based surveillance environment to a satellite-based navigation/ADS environment. This paper provides an initial system description of the ADS-Mode S concept, describes surveillance applications that it will satisfy, and gives system performance estimates.

MODE S SQUITTER

A Mode S squitter is currently in operational use by TCAS. Its performance is well understood by virtue of the design and validation of TCAS and from years of operational use. The MIT Lincoln Laboratory concept for ADS-Mode S proposes that a new Mode S squitter be created to provide for the ADS function. This new squitter would be a longer version of the present one. The current and proposed squitters are described in this section.

Current Mode S Squitter

The current Mode S squitter is a 56-bit transmission used by TCAS to detect the presence of nearby aircraft equipped with Mode S transponders. The squitter contains the Mode S address of the aircraft and is broadcast at a 1 Hz rate by all Mode S transponders. The broadcast is made on the 1090 MHz frequency utilized by all civil aviation transponders.

ADS-Mode S Squitter

For ADS, a new squitter would be created by adding an ADS message field to the current squitter format. Since the Mode S message protocol defines both 56-bit and 112-bit replies, the ADS-Mode S squitter would use the 112-bit format as shown in Figure 1. This new format thus allows 56 bits for the ADS data.

Three types of ADS messages are envisaged, two provide aircraft position information and the third provides the ICAO identification of the aircraft. One of the position messages would be used by aircraft in flight and the other applies to aircraft on the airport surface. The aircraft position messages would be transmitted at an average rate of 2 Hz and the identification message would be transmitted on average once every 5 seconds. The actual spacing between squitters would be randomized slightly to prevent synchronous interference between two aircraft. The spacing between the position squitters would be uniformly

---

* This work was sponsored by the Federal Aviation Administration under contract numbers DFTA01-92-Z-02010 and DFTA01-93-A-02012.

0-7803-1343-7/93 $3.00 © 1993 IEEE

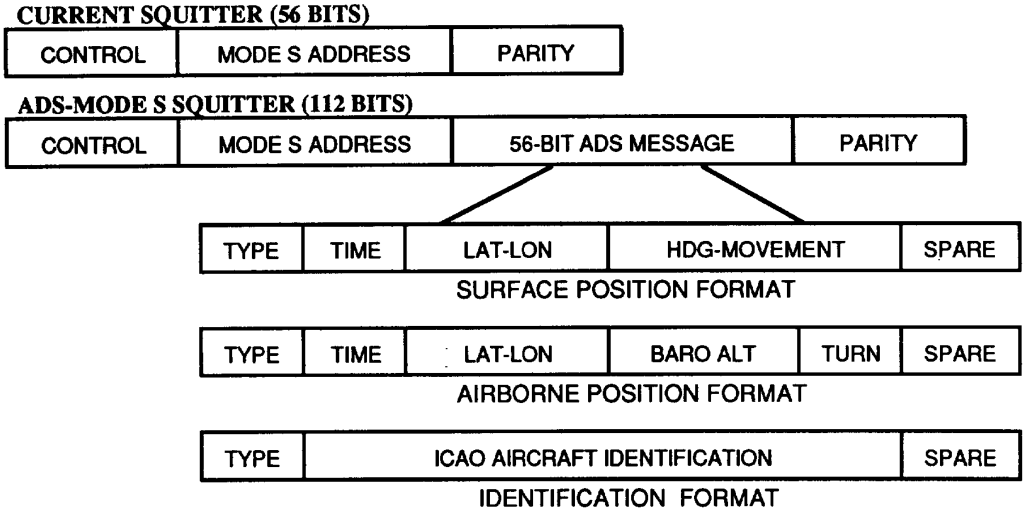

Figure 1. Current and Proposed Squitter Formats.

distributed between 0.4 and 0.6 seconds and a similar jitter would be used for the identification squitter. Only one type of position message would be in use at a given time, with the type depending on whether the aircraft is in the air or on the surface. The identification message would be radiated in both cases.

The airborne position message, shown in detail in Table 1, contains a 4-bit message type field, a one bit time field, 18 bits each for latitude and longitude, 12 bits for barometric altitude, one bit for use as a turn indicator, and 2 spare bits. The type field would be used not only to specify which of the three types of ADS messages is being transmitted but to also provide information as to the source of the position information, e.g., GPS, differential GPS (DGPS), etc. To minimize the number of bits required to provide the time associated with a position fix, GPS units would be required to perform the position fix each second on a GPS second mark or to extrapolate the measurement to the second mark. Since the airborne squitter is transmitted twice per second, the only ambiguity on the time of measurement at the receive station would be whether the measurement was made on the current GPS second or on the previous one. The ambiguity is due to processing and transmission delays. A bit that specifies an even or odd GPS second should be sufficient to resolve the ambiguity as long as the receive station is also using GPS time. The bits allotted to latitude and longitude provide a resolution of 14 feet with an unambiguous zone 600 nmi wide. Altitude is provided with a nominal resolution of 25 feet. This value would be obtained from a barometric altimeter to maintain compatibility with other aircraft. The turn indicator would permit quick identification of an aircraft maneuver.

Table 1. ADS -Mode S Airborne Position Format

FIELD	# BITS	LSB	VALUE/RANGE
TYPE	4	–	2 - DGPS 4 - GPS
TIME	1	1 sec	ODD/EVEN
LATITUDE	18	14 ft	0 to 600 nmi
LONGITUDE	18	14 ft	0 to 600 nmi
ALTITUDE	12	25 ft 100 ft	-1 to 56 kft 56 to 127 kft
TURN INDICATOR	1	–	0 - NOT TURNING 1 - TURNING
SPARE	2	–	–
TOTAL	56		

The surface position format is very similar to the airborne one. The main difference is that in place of altitude, the surface message provides information on heading and speed. A change would also be made to the latitude and longitude encoding. Since the unambiguous range can be much less for an aircraft on the surface than for one in the air, this range is reduced to provide a position resolution of approximately 4 feet.

Providing aircraft identification (e.g., AA 123) would be beneficial to TCAS and CDTI (Cockpit Display of Traffic Information) operations. Since aircraft identification rarely changes in flight, it would only be transmitted once every 5 seconds. There would be no problem is associating aircraft position to aircraft identification since all three ADS messages contain the Mode S address of the aircraft.

ADS-MODE S SURVEILLANCE APPLICATIONS

As ADS-Mode S was being developed, it became clear that its broadcast mode of operation combined with the navigational accuracy available from GPS or DGPS permit ADS-Mode S to be used for many different types of surveillance. These can be grouped into air-to-ground surveillance, surface surveillance, and air-to-air surveillance. This section briefly describes how ADS-Mode S might be used for these surveillance applications. The performance of ADS-Mode S will be estimated in the next section.

Air-to-Ground Surveillance

The concept for ADS-Mode S air surveillance is illustrated in Figure 2. Terminal area surveillance would be provided by a ground station that has an omnidirectional antenna pattern in azimuth. Such an antenna would provide surveillance coverage out to 50 nmi range. The accuracy of GPS depends on whether selective availability is turned on or not. Selective availability is the name of a technique used by the Department of Defense to intentionally degrade the performance of GPS for security reasons. Even with selective availability turned on, however, the accuracy of GPS is sufficient to meet most terminal area surveillance needs. For those applications that require additional accuracy, such as Precision Runway Monitoring (PRM), differential GPS can be used. The ground stations would use an uplink broadcast to provide differential corrections to the aircraft. This uplink would be transmitted at 1030 MHz.

By using a 6-sector antenna at the ground stations, surveillance out to 100 nmi range can be accommodated. Multiple stations of this type could be used to replace an en route beacon interrogation radar that has a 200 nmi range. In most of the United States, the 100 nmi range of the ADS-Mode S system would allow them to be located at existing FAA facilities, e.g., RCOs (Remote Communications Outlets) and VORs (VHF Omnidirectional Range) sites.

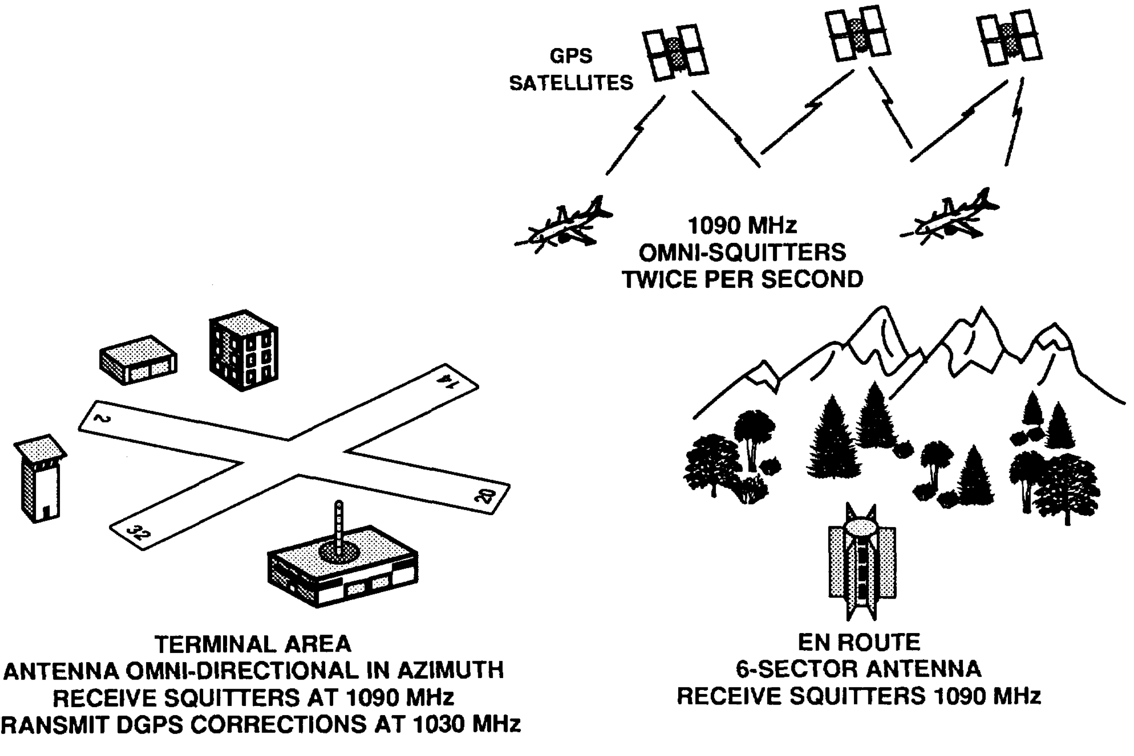

Figure 2. Air Surveillance with ADS-Mode S.

Surface Surveillance

The ADS-Mode S surface position message would be radiated while aircraft are operating on runways and taxiways. These messages would be received by ground stations located around the periphery of the airport. Multipath interference and blockage from buildings may prevent any one ground station location from reliably receiving squitters from all of the primary movement areas of a large airport but a few additional locations should provide sufficient diversity.

The use of DGPS will be necessary on the surface to provide the required position accuracy. As for PRM, the differential corrections would be broadcast from the ground stations at 1030 MHz. The availability of a transmit capability in the ground stations means that Mode S data link service can be used to provide a general purpose data link in support of surface automation.

Air-to-Air Surveillance

Since a broadcast mode is used to transmit the ADS-Mode S messages, they can be received not only by ground stations but also by nearby aircraft. This allows the use of ADS-Mode S for both TCAS and CDTI. With selective availability off, it is expected that TCAS could perform all of its surveillance passively. In such a case, the only time that TCAS would be required to transmit would be when it is performing coordination for an avoidance maneuver. When selective availability is on TCAS could still remain passive most of the time.

ADS-Mode S may provide a new basis for TCAS 3. This version of TCAS will allow horizontal conflict resolution maneuvers. It requires accurate knowledge of the azimuth of nearby aircraft as well their range and altitude. GPS-based navigation should provide the required accuracy.

General aviation aircraft would not require a TCAS system but could benefit from CDTI. CDTI is a much simpler system than TCAS. It provides a cockpit display of nearby aircraft but does not issue resolution advisories

ADS-MODE S PERFORMANCE ESTIMATES

A surveillance system for aircraft must not only have high reliability, but it also must be sufficiently accurate, have a large enough coverage area, and accommodate a sufficiently large aircraft population for the surveillance application for which it is intended. In addition, for a system that uses a portion of the electromagnetic spectrum, the necessary bandwidth must be available.

Reliability

The ADS-Mode S squitter uses a Mode S reply waveform operating at 1090 MHz. The data are encoded using pulse position modulation (PPM) at a one megabit per second rate. The use of PPM in combination with the inclusion of a 24-bit parity field in each of the reply messages provides significant resistance to interference. Extensive testing and years of experience with TCAS have shown this waveform to be highly reliable. More information on Mode S waveforms may be found in Ref. 2.

Accuracy

The accuracy of an ADS-Mode S surveillance system depends on the source that it uses to obtain the navigation information and on the precision with which the position information is encoded in the ADS-Mode S messages. The encoding of the ADS-Mode S position messages was described earlier. The airborne message provides latitude and longitude to a resolution of 12 feet and the surface message has a resolution of 4 feet. Altitude is encoded with the same precision (nominally 25 feet) used by today's transponders.

The navigation data will be assumed to come from a combination of GPS and a barometric altimeter. With selective availability on, the accuracy of the horizontal position estimates provided by GPS is better than 100 meters 95% of the time and local area differential GPS can provide a horizontal accuracy on the order of a few meters (Ref. 3). When combined with the encoding resolution in the ADS-Mode S messages, GPS/DGPS should support the surveillance applications mentioned in the previous section.

Surveillance Range

TCAS will be used as a design baseline to determine the surveillance range for ADS-Mode S since TCAS uses the same type of transponder that ADS-Mode S will employ. The air-to-air surveillance range for ADS-Mode S will, therefore, be identical to that of the current TCAS (10-15 nmi). The air-to-ground surveillance range will depend on the characteristics of the ground receiver and will be discussed below. For airport surface surveillance, the free space operating range of a system is not as much a factor as its performance in an environment containing numerous strongly reflective surfaces and obstructions. A thorough analysis of ADS-Mode S performance in such an environment is underway. Based on early results it is expected that more than one receive station will be required to cover the primary movement areas of a major airport. Past measurements taken with Mode S waveforms at Logan International Airport in Boston, Massachusetts suggest that approximately four ground stations would be required at that site (Ref. 4.)

For air-to-ground surveillance, an operational range of 50 nmi would satisfy terminal area surveillance needs and a range of 100 nmi would be adequate for en route surveillance. Improvements over the TCAS operating range are possible by using a properly designed ground station. The ground station could have a better receiver noise figure, higher antenna gain, and less cable loss than its airborne counterpart.

The effect that such improvements could have on the air-to-ground surveillance range are indicated in Table 2. This table shows link budget estimates for the terminal area and en route cases and also provides the current TCAS link margin for comparison. The terminal area and en route examples differ only in terms of the gain of the receive antennas. For terminal area surveillance a 5-foot vertical aperture cylindrical antenna is assumed that produces a beam omnidirectional in azimuth with 4 dB of gain. This antenna will be referred to simply as an omni antenna. For en route surveillance a 6-sector antenna is envisaged as shown in Figure 2. Each sector would have the same vertical aperture as the terminal area antenna but the horizontal beamwidth would be reduced providing additional antenna gain. Good link margins are obtained for both cases: 12 dB for terminal area surveillance and 9 dB for en route surveillance.

Table 2. Air Surveillance Link Budget

	TCAS	Terminal Area (Omni Antenna)	En Route (6-Sector Antenna)
Reference Range (nmi)	10	50	100
Transmit Power (dBm)	54	54	54
Transponder Antenna Gain (dB)	0	0	0
Free Space Path Loss (dB)	-118.5	-132.5	-138.5
Receive Antenna Gain (dB)	0	4	7
Receive Cable Loss (dB)	-3	-2	-2
Receive Power (dBm)	-67.5	-76.5	-79.5
Min Power for Detection (dBm)	-77	-88.5	-88.5
Link Margin (dB)	9.5	12.0	9.0

Operating Capacity

The number of aircraft that can be accommodated by an ADS-Mode S system is limited by interference on the 1090 MHz frequency. This frequency is reserved primarily for beacon radar use and the following sources of interference are present: transponder replies to ATCRBS (Air Traffic Control Radar Beacon System) interrogations, 56-bit ("short") Mode S replies, and 112-bit ("long") Mode S replies. The ADS-Mode S squitters are a subset of the long Mode S replies.

The arrival of the different types of 1090 MHz messages at a receive station in a particular time window will be modeled as a Poisson process. An ADS-Mode S squitter will be assumed to be correctly received if and only if the following conditions are met: (1) no other Mode S replies overlap with it in time; and (2) at most one ATCRBS reply overlaps with it in time. The first of these criteria is conservative since there is a good chance that one of the overlapping replies (the one with the higher signal strength) will be correctly decoded. The second criteria stems from the fact that the Mode S error correction capability was designed in part to survive one overlapping ATCRBS reply.

With these assumptions the probability, p, that an ADS-Mode S squitter is correctly received can be expressed by:

$$p = (1+t_1 n_1 m) e^{-t_1 n_1 m} * e^{-t_2 n_2 m} * e^{-t_3 n_3 m},$$

where, n_1, n_2, n_3 refer to the average number of ATCRBS, short Mode S, and long Mode S replies per aircraft per second, respectively; t_1, t_2, and t_3 represent the length of time that the ADS-Mode S squitter is vulnerable to the start of ATCRBS, short Mode S, and long Mode S replies, respectively; and, m is the total number of aircraft that can generate interfering replies (some of these aircraft may be beyond the nominal operating range of the surveillance system).

The ATCRBS replies are 20 μsec in duration and the short and long Mode S replies (including an 8 μsec preamble) are 64 and 112 μsec long, respectively. Since the long squitter is 120 μsec long, the values for t_1, t_2, and t_3 are given by:

$$t_1 = 0.000140 \text{ sec},$$
$$t_2 = 0.000184 \text{ sec},$$
$$t_3 = 0.000240 \text{ sec}.$$

To obtain capacity estimates, it is necessary to specify a reliability level, a surveillance update rate, and reply rates for the different types of 1090 MHz transmissions. Table 3 presents capacity estimates for a reliability greater than or equal to 99.5% of obtaining one or more target updates in 9 ADS-Mode S squitter attempts (i.e., in approximately 5 seconds). Three different levels of aircraft transponder reply rates are considered. The first assumes that each aircraft replies 120 times per second to ATCRBS interrogations, the second assumes 60 ATCRBS replies per aircraft per second, and the third assumes no ATCRBS replies. The number of Mode S replies in all cases is assumed to be 8 short replies and 6 long replies per aircraft per second. The first case represents an extremely high ATCRBS reply environment and the second a moderately high estimate. The third case provides an indication of how the capacity might improve as the ATCRBS interrogators are replaced by Mode S interrogators as is currently planned.

Even with the extremely high reply rates assumed for Case 1, moderate aircraft densities can be accommodated. With the omni antenna, 86 aircraft can operate with a reliability of 99.5% for this case. Each sector of the 6-sector antenna can also

Table 3. Air Surveillance Operational Capacity
(Update Rate ~ 5 sec, Reliability ≥ 99.5 %)

Case	Replies/Aircraft/Second			Aircraft Capacity	
	ATCRBS	Short Mode S	Long Mode S	Omni Antenna	6-Sector Antenna
1	120	8	6	86	215
2	60	8	6	140	350
3	0	8	6	278	695

accommodate 86 aircraft for Case 1. The total capacity for the 6-sector antenna will depend on how the aircraft are distributed in azimuth. In Table 3, it is assumed that a 6-sector antenna will provide a factor of 2.5 improvement in total aircraft capacity, thus allowing for 215 aircraft in Case 1 and for nearly 700 aircraft in Case 3.

On the surface, ADS-Mode S transponders do not respond to ATCRBS or to Mode S all call interrogations and, in addition, the short squitter is not broadcast. The number of interfering transmissions would, therefore, be much lower on the surface compared to the airborne situation. By using properly designed receive antennas only a very limited number of airborne aircraft would generate interfering replies. Assuming that all interference originates from other ADS-Mode S squitter transmissions, there would be on average 2.2 long Mode S replies per aircraft per second (two surface ADS squitters each second and one identification squitter every 5 seconds).

Even in the absence of interference from other Mode S transmissions, multipath may prevent a surface squitter message from being correctly received. Testing is planned to quantify this effect. Herein, it will be assumed that 5% of all squitters are lost because of multipath. The remaining squitters will be successfully decoded if they do not overlap in time with the long Mode S transmissions from other aircraft on the surface. With these assumptions, a single receive antenna can accommodate over 250 aircraft with a reliability of 97% of obtaining at least one update on each target every 1.2 seconds (i.e., in two squitter attempts). As was the case for air surveillance, sectored antennas may be used to increase the overall surveillance capacity.

Channel Occupancy

As noted above, ADS-Mode S transmissions are not the only ones using the 1090 MHz frequency. The effect that the ADS-Mode S squitter has on other users of this frequency will be discussed in this sub-section. If ADS-Mode S were to present a problem, it would do so in a high density environment and it is this case that will be treated.

The total occupancy per aircraft with and without the ADS-Mode S squitters is shown in Table 4. The reply rates assumed are those from Case 1 of Table 3. The ADS-Mode S squitters add an average of 2.2 long Mode S transmissions per aircraft per second, increasing the channel occupancy by 264 µsec. The total channel utilization per aircraft is increased from 0.3368% without the ADS-Mode S squitters to 0.3632% with them. This is considered to be a tolerable increase. In fact, since ADS-Mode S will make it possible for TCAS to operate passively most of the time, it is possible that in high density environments the total channel occupancy will actually be reduced.

Implementation Issues

When developing a new surveillance system such as ADS, the question of how to transition to it must be addressed. Since ADS-Mode S is based on a minor modification of the existing Mode S transponder, implementing such a system should be relatively straightforward. Standards for Mode S exist and these would only require a modification to include the new squitter format. For TCAS to benefit from the ADS-Mode S information, the TCAS standards would also require some minor modifications. ADS standards are currently in development and would have to address ADS-Mode S.

Table 4. ADS-Mode S Impact on Channel Occupancy

Type of Transmission	Ave. Number per Aircraft per Second	Occupancy (µsec)
ATCRBS Replies	120	2400
Short Mode S Replies	7	448
Short Mode S Squitter	1	64
Long Mode S Replies	5.8	456
Total Current Channel Occupancy		**3368**
ADS Mode S Squitter	2.2	264
Occupancy With ADS Squitter		**3632**

An aircraft that equips with an ADS-Mode S transponder would be fully compatible with existing beacon-based surveillance systems. This would allow ADS-Mode S to be seamlessly phased in over a period of several years. In addition, aircraft that now have data link transponders could be upgraded to ADS-Mode S by means of a software change only.

Summary

ADS-Mode S provides for a natural transition from a beacon-based surveillance system to an ADS system. A software modification is all that is required to upgrade an existing data link transponder for the ADS application. Standards for Mode S and TCAS already exist and would require only minor modifications to support ADS-Mode S. With GPS/DGPS as the source of the navigation data, ADS-Mode S can support many types of surveillance needs including: en route surveillance; terminal area surveillance; precision runway monitoring; surface surveillance; TCAS; and CDTI.

Acknowledgments

The original concept for ADS-Mode S was first proposed by Paul R. Drouilhet, Assistant Director of MIT Lincoln Laboratory. Under FAA sponsorship, Lincoln Laboratory established a small study team to define the characteristics and estimate the performance of ADS-Mode S. In addition to the authors, the study team was composed of the following staff members of Lincoln Laboratory: Edward T. Bayliss, William H. Harman, George H. Knittel, David Reiner, and M. Loren Wood. Vincent A. Orlando served as chairman of the study. Valuable contributions to the development to the concept were also made by P. Douglas Hodgkins of the FAA.

REFERENCES

1. R. Lam, "Pacific ADS: Fast Track to Reality," *ICAO Journal*, March 1992, pp. 8-11.

2. V. A. Orlando and P. R. Drouilhet, "Mode S Beacon System: Functional Description," Project Report ATC-42, Rev. D, MIT Lincoln Laboratory, (29 August 1986), FAA/PM-86/19.

3. T. Logsdon, The NAVSTAR Global Positioning System, (Van Nostrand Reinhold, New York, New York, 1992).

4. M. L. Wood, "Propagation of Mode S Beacon Signals on the Airport Surface," Lincoln Laboratory Journal, Vol. 2, Number 3 (1989), pp. 397-410.