GPS-Squitter: System Concept, Performance, and Development Program

Vincent A. Orlando, George H. Knittel, and Robert E. Boisvert

■ GPS-Squitter merges the capabilities of Automatic Dependent Surveillance (ADS) with the Mode S beacon system. In ADS, an aircraft determines its position on board by using satellite navigational data from a system such as the Global Positioning System (GPS). The information is then broadcast to ground and airborne users to provide surveillance of the aircraft. In GPS-Squitter, an aircraft would transmit the ADS information by using the Mode S squitter—a spontaneous periodic broadcast transmitted by all Mode S transponders. Currently, the Mode S transponders emit a 56-bit squitter once per second, and the squitters are used by the Traffic Alert and Collision Avoidance System (TCAS) to acquire the 24-bit address of the aircraft. For the GPS-Squitter system, the squitter broadcast is extended to 112 bits to provide for the transmission of a 56-bit ADS message field.

This article defines the GPS-Squitter concept, describes its principal surveillance and data-link applications, and provides estimates of the expected performance in future moderate-to-high-density environments. The program under way to develop this concept is also described together with examples of measured performance data.

The International Civil Aviation Organization has defined the Future Air Navigation System (FANS)—a concept for communications, navigation, and surveillance for the next century. A cornerstone of FANS is the increasing reliance on satellite-based navigation systems such as the Global Positioning System (GPS). With satellite navigational data, the position of an aircraft can be derived on board the vehicle, and this information can be transmitted via a data link to a ground station to aid the station in the surveillance of aircraft. This technique is known as automatic dependent surveillance (ADS).

Under the FANS concept, 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. Because such general equipage will take many years, early implementation is expected to take place in regions where other surveillance techniques are not practical—for example, over the ocean and in remote areas. In fact, planning is currently under way for ADS to support air traffic control (ATC) management of oceanic routes. Significant economic benefits are anticipated as a result of the reduction in aircraft separation (and the resultant increase in air-route capacity) made possible by ADS. In this ADS application, an aircraft is connected with the controlling oceanic ATC facility via a point-to-point link.

The use of ADS in terminal and overland areas requires a more general form in which the aircraft broadcasts its position in an omnidirectional fashion. With this type of broadcast, one ADS transmission can serve the surveillance needs of multiple ground ATC and airborne collision-avoidance ac-

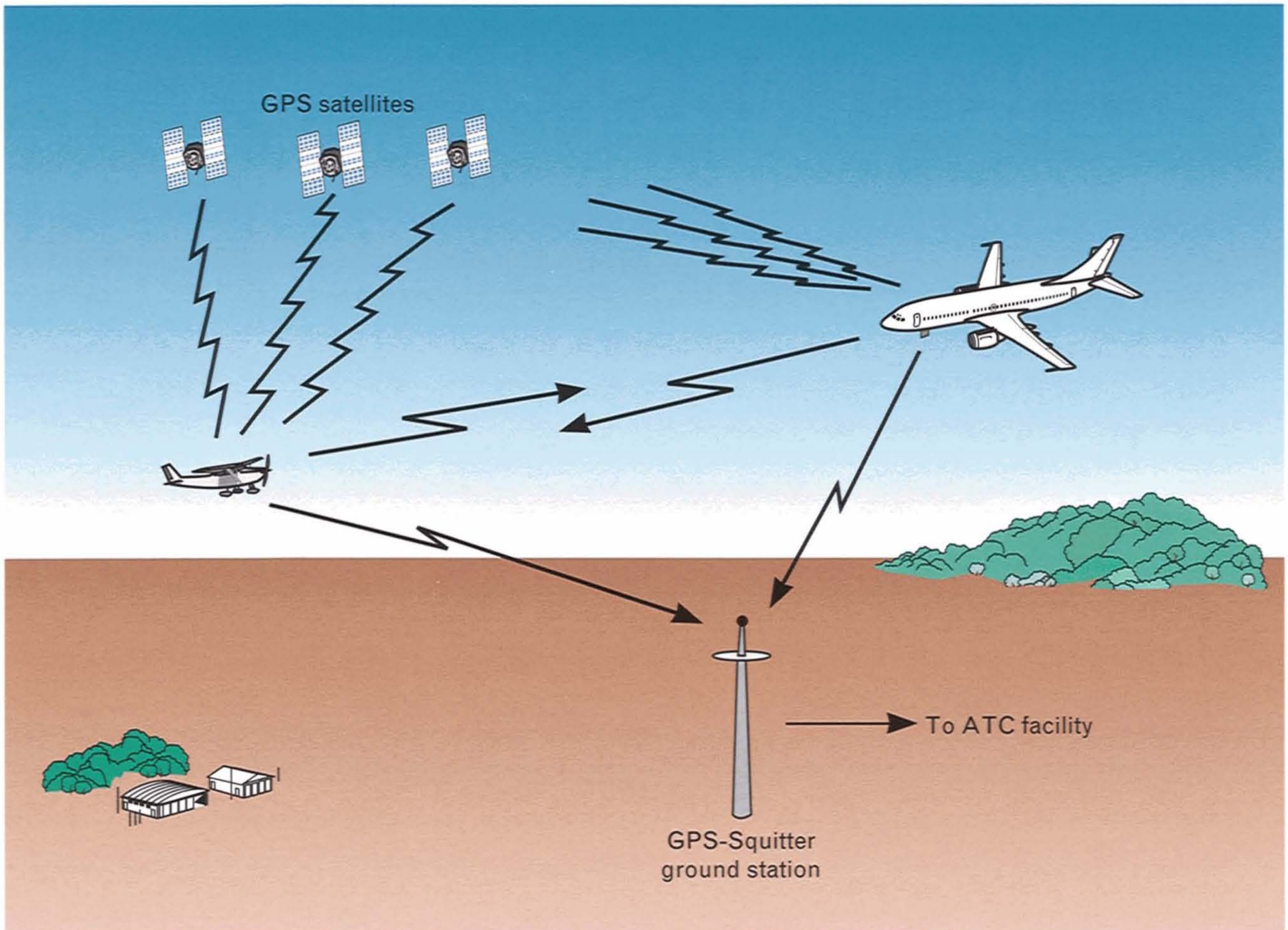


FIGURE 1. GPS-Squitter system concept. Aircraft equipped with GPS receivers determine their position from GPS satellite transmissions. The aircraft broadcast this position information in an omnidirectional azimuth pattern. These transmissions, called squitters, are received by simple omnidirectional or sector-beam antennas on the ground. The ground stations use the squitter information to provide ground-to-air surveillance of the aircraft. The squitters are also received by other aircraft for air-to-air surveillance.

tivities simultaneously.

GPS-Squitter is a system concept (Figure 1) that merges the capabilities of ADS with that of the Mode S beacon radar [1, 2]. The result is an integrated concept for seamless surveillance that permits equipped aircraft to participate in ADS or beacon ground environments. GPS-Squitter is a natural way for the National Airspace System (NAS) surveillance to make the transition from a ground-based beacon radar system to a GPS-ADS–based environment. In addition, GPS-Squitter offers several other possibilities for significant benefits to the NAS.

System Concept

In the current Mode S design, each Mode S transponder radiates its unique Mode S address randomly in an omnidirectional azimuth pattern once per second. Called squitters, these transmissions contain 56 bits, have a duration of about 60 μsec, and are broadcast on the Mode S transponder reply frequency of 1090 MHz.

Table 1 contains details of the current Mode S squitter, which is used by the Traffic Alert and Collision Avoidance System (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 56-bit squitter data, and uses this address as the basis for discrete interrogation, as required, to perform surveillance of Mode S–equipped aircraft.

It is important to note that the Mode S squitter has been in operational use with TCAS since the initial implementation in 1990. Beginning 31 December 1993, TCAS has been operating on all commercial aircraft with more than thirty passenger seats in the United States. Consequently, the performance of the Mode S squitter is well understood from the design and validation of TCAS as well as from substantial experience with TCAS as an operational system.

In addition to the 56-bit format used by TCAS, the Mode S message protocol also defines 112-bit reply formats. The GPS-Squitter approach uses one of these 112-bit formats, as described in Table 2. The 112-bit format creates a 56-bit message field for ADS data, with all other fields remaining the same as in the shorter 56-bit format. There are three types of ADS message fields: one for air surveillance, one for surface surveillance, and one for flight identification. On average, an aircraft transmits either the first or the second type of squitter once every 0.5 sec, and the third type of squitter once every 5 sec.

In operation, aircraft equipped with a Mode S transponder and a GPS receiver determine their position once every second, and 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 every second for compatibility with TCAS. On the ground, simple omnidirectional or sector-beam antennas receive the long squitters, and the ground stations use these squitters to provide ground-to-air surveillance of the aircraft. In addition, TCAS aircraft can be modified to receive long squitters to support passive surveillance of Mode S aircraft.

Surveillance Applications

The most important surveillance applications of GPS-Squitter are

- Air surveillance from a terminal area or en route ground station. The 3-to-5-m position accuracy of local-area differential GPS (DGPS) could also enable precision runway monitoring (PRM). In DGPS, the GPS data are adjusted with correction factors from ground stations whose exact locations are known.

Table 1. Format for Short Squitter Used in TCAS

Function	*Number of bits*
Control	8
Mode S address	24
Parity	24
Total	*56*

Table 2. Formats for Long Squitters Used in GPS-Squitter

Function	*Number of bits*
Control	8
Mode S address	24
ADS message	
Air-surveillance format	
Type/figure of merit	5
Surveillance control	2
Turn	1
Barometric altitude	12
Spare	1
Time	1
Latitude	17
Longitude	17
Total	*56*
Surface-surveillance format	
Type/figure of merit	5
Movement	7
Track angle	7
Spare	2
Time	1
Latitude	17
Longitude	17
Total	*56*
Flight-identification format	
Type/figure of merit	5
Not used	3
Aircraft identification	48
Total	*56*
Parity	24
Total	*112*

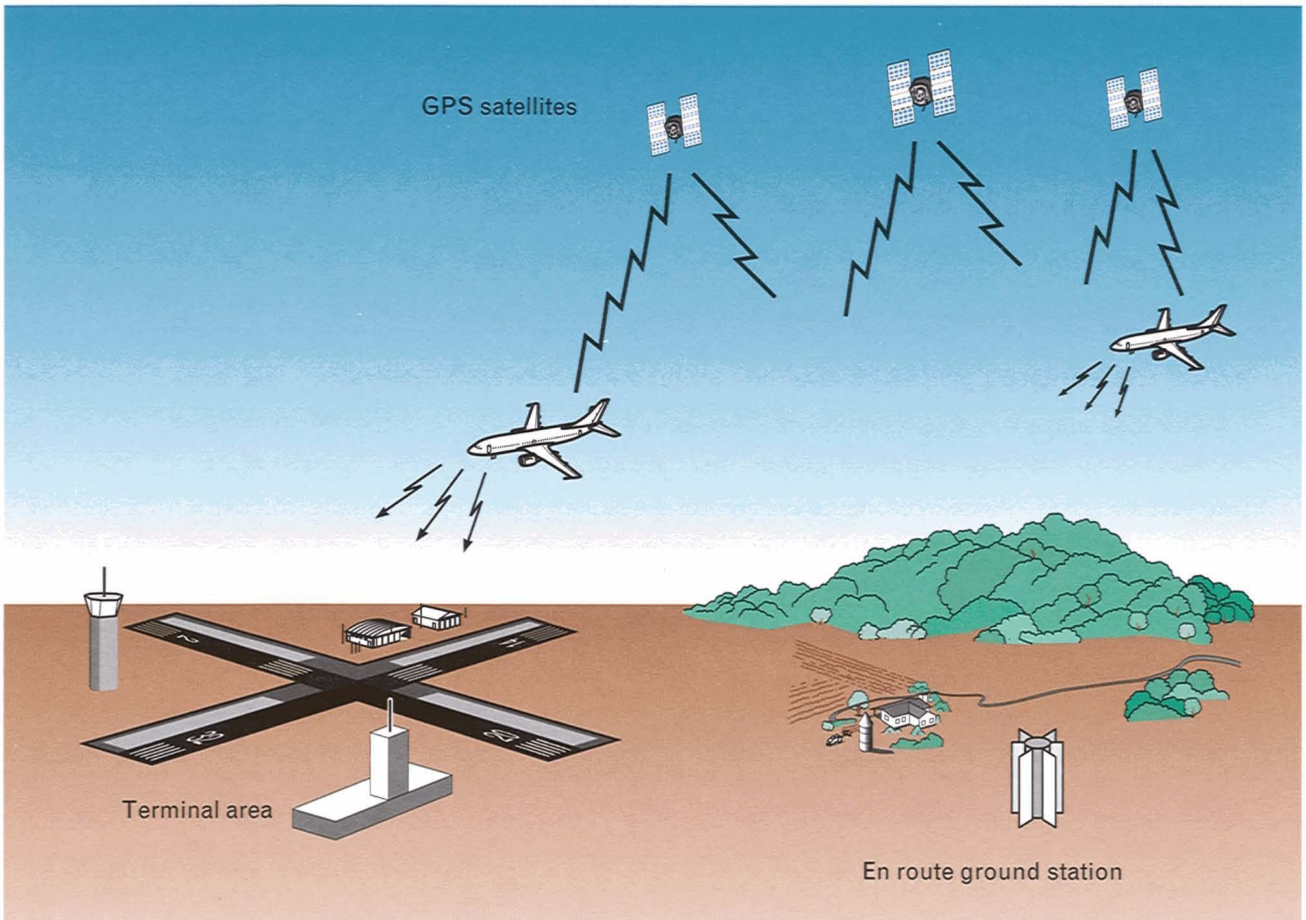


FIGURE 2. Air surveillance from a terminal area and from an en route ground station with GPS-Squitter. Using the GPS satellites, aircraft determine their positions and broadcast this information in squitters at 1090 MHz twice per second. The squitters are received by an omnidirectional antenna at the terminal area and by a six-sector antenna at an en route ground station. Both ground stations can provide a data-link service to the aircraft at 1030 and 1090 MHz.

- Surface surveillance of runways and taxiways with the accuracy provided by DGPS.
- Air-air surveillance for improved TCAS operation and for the cockpit display of traffic information (CDTI).

Air Surveillance from the Ground

Air surveillance from both a terminal area and an en route ground station are shown in Figure 2. Using the GPS satellites, aircraft determine their positions and broadcast this information in squitters, which are received by terminal and en route ground stations. The terminal antenna—a single omnidirectional antenna with a low-noise front end and a 1.5-kW transmitter—has a squitter-reception range and two-way data-link range of 50 nmi. The antenna for the en route station—a six-sector high-gain antenna with six independent low-noise receivers and one 1.5-kW transmitter—has a downlink and uplink range of 100 nmi. Antennas such as the six-sector antenna shown in Figure 2 can also be used in areas of high traffic density to limit the number of aircraft being processed by any one receiver.

Both terminal and en route antennas provide Mode S data-link service at 1030 and 1090 MHz. In addition, the terminal stations provide uplink DGPS corrections for PRM and for GPS-based category 1 (CAT 1) precision approach [3].

Airport Surface Surveillance

Airport surface surveillance is illustrated in Figure 3. An aircraft operating on a runway or taxiway transmits squitters (containing the vehicle's DGPS position), which are received by several stations around the periphery of the airport. Two such stations are shown in Figure 3, but the actual number for a particular airport depends on the squitter-reception performance in the environment of that airport surface. Measurements and studies are under way to obtain both better estimates of this performance and better predictions of the ground-station requirement for arbitrary airport configurations.

TCAS Use of GPS-Squitter Data

The aircraft position information in GPS-Squitter data can also be used for significantly improving the operation of TCAS.

For security reasons, the Air Force intentionally perturbs the accuracy of GPS through a technique called *selective availability* [4]. Analysis of TCAS operation indicates that, if selective availability is used (as it is today), GPS-Squitter will be able to support passive surveillance of Mode S aircraft that have a tau, i.e., a time of closest approach, of at least 40 sec. Experience with TCAS in normal operational service [5] indicates that, on average, an intruder with a tau of about 40 sec is observed once every 1 to 2 hr per TCAS-equipped aircraft. Thus GPS-Squitter will permit TCAS to perform most of its surveillance passively. If selective availability is not used, 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 the system is performing coordination for an avoidance maneuver. Experience indicates that this situation occurs only once every 45 hr per TCAS-equipped aircraft.

In addition to surveillance benefits, the ADS position information can be used with miss-distance filtering to reduce the nuisance alert rate for TCAS II, as discussed in the article "TCAS: Maneuvering Aircraft in the Horizontal Plane," by D.W. Burgess et al., in this issue [6]. GPS-Squitter also provides the basis for TCAS IV, the version of TCAS that incorporates horizontal avoidance maneuvers. In fact, the use of ADS position information from intruder aircraft provides a more achievable basis for implementing horizontal avoidance maneuvers than the alternative of precision antennas to measure the bearing angles of intruder aircraft [7].

CDTI Using GPS-Squitter

Cockpit display of traffic information (CDTI) is feasible for aircraft equipped with a 1090-MHz receiver. Such aircraft would listen to long squitters from nearby aircraft and display the positions and identities of those vehicles on a small cockpit display. A receiver that is equivalent to a TCAS receiver could support CDTI out to a range of 14 nmi. In all but the highest interference environments, this range can be extended to 30 nmi through the addition of a low-noise front end to the receiver. TCAS receivers, which operate at 1090 MHz, would require only small modifications for CDTI operation. Other aircraft would have to be fitted with 1090-MHz receivers to realize this benefit.

Other Surveillance Applications

GPS-Squitter offers a low-cost means of surveillance for small terminals that do not qualify for high-cost ground beacon equipment. GPS-Squitter can also be used to fill in the gaps between en route ground stations in mountainous or remote areas. TCAS II units sell for about \$100,000, and a simple omnidirectional ADS ground station that is a modified TCAS unit is expected to be comparably priced.

Data-Link Capability

ADS ground stations are intended to have two-way Mode S data-link capability. This capability would supplement that of the 143 Mode S radars being commissioned and could extend data-link coverage down to a much lower altitude.

The Mode S data link is an integral part of GPS-Squitter because the data link is used to obtain a GPS-Squitter aircraft's Mode A code—a 12-bit binary code (4096 code combinations) that is the current basis for ATC aircraft identification. The Mode A code is utilized by the current Air Traffic Control Radar Beacon System (ATCRBS) as well as by Mode S, the next-generation beacon system.

A second possible application of the GPS-Squitter data-link capability is the broadcast of DGPS corrections to support special CAT I precision approaches.

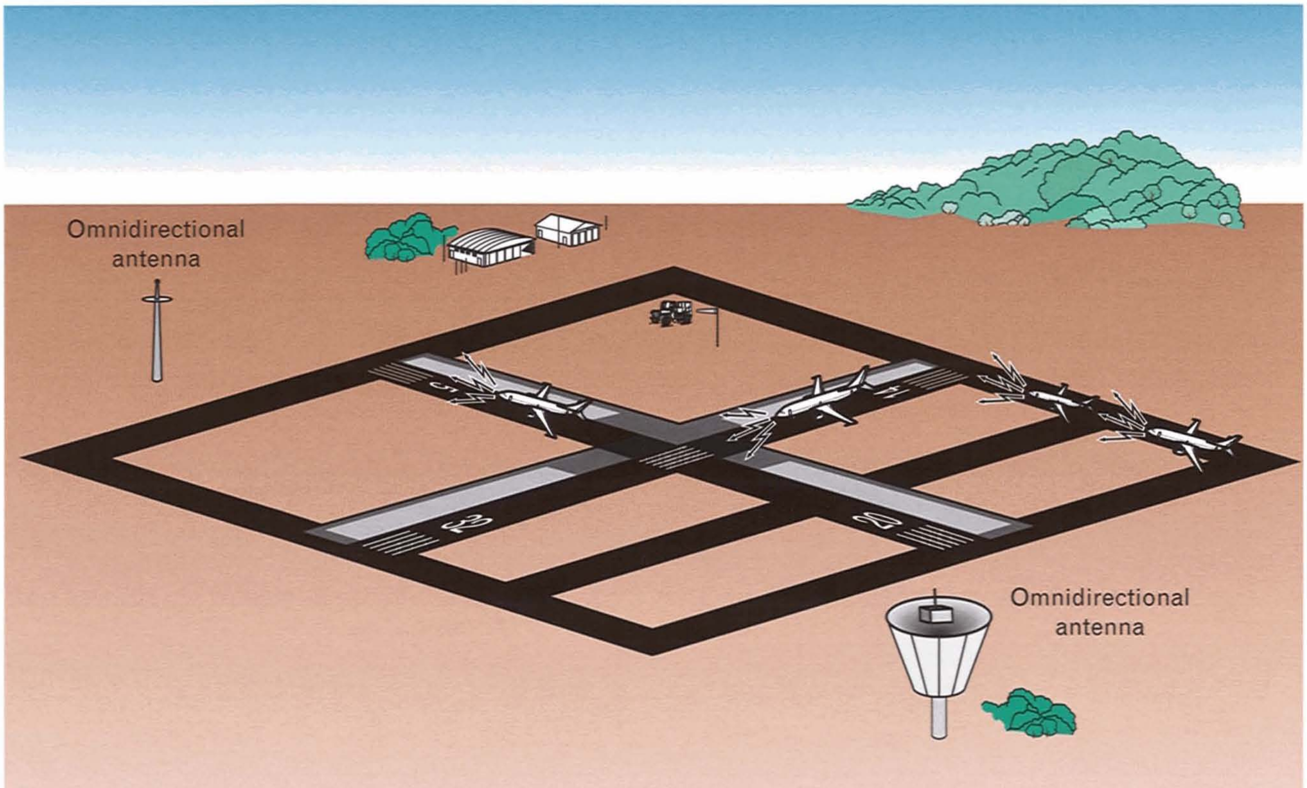


FIGURE 3. Airport surface surveillance with GPS-Squitter. An aircraft operating on a runway or taxiway transmits squitters containing the vehicle's differential GPS (DGPS) position. The squitters, which are transmitted at 1090 MHz twice per second, are received by ground stations around the periphery of the airport. Two such stations are shown in the figure, but the actual number for a particular airport depends on the squitter-reception performance in the environment of that airport movement area. The stations can also provide a data-link service to the aircraft at 1030 and 1090 MHz. (Note: In DGPS, an aircraft's GPS position accuracy is improved by the use of correction factors from ground stations whose exact locations are known.)

The characteristics of the Mode S data link and its suitability for DGPS service have been investigated by the RTCA Special Committee 159, an organization dedicated to the requirements and technical concepts for aviation. The committee produced the Minimum Aviation System Performance Standards (MASPS) [8], which identified Mode S broadcast and the VHF data link as the two candidates for DGPS service. Other data-link applications include the transmission of graphical weather products and other similar services.

The transmit/receive protocol inherent in Mode S will permit the independent measurement of range, thus allowing verification of the passively received ADS position reports. This verification would be done when an aircraft is first observed by a ground station or TCAS and would be repeated at some low rate to monitor the validity of the GPS-derived position reports. In the event of a GPS failure on an aircraft, surveillance could still be maintained with range measurements from two ground stations.

Critical Issues

In December 1992, Lincoln Laboratory commenced a development program for the GPS-Squitter concept. The initial focus of the program was a critical-issues study, a system design, and the surface-surveillance application. For the critical-issues study, the following subsections present the investigated topics and results.

Message Capacity

As shown in Table 2, there are three types of ADS message fields. The different formats serve different purposes: air surveillance, surface surveillance, and flight identification.

The air-surveillance message format is used to relay the positions of airborne aircraft. The format contains 5 bits for the message type/figure of merit (FOM) field, 2 bits for a surveillance control field, 12 bits for barometric altitude, 1 bit for a time field, and 17 bits each for latitude and longitude. The message type/FOM field indicates the accuracy of the reported navigation position fix. A 1-bit field is sufficient for the time because GPS units will be required to perform a position fix every second on a GPS second mark. Units that cannot support this timing will be required to extrapolate to the next GPS second mark. Because the squitter is transmitted twice per second, the only ambiguity in the time of a measurement is whether the measurement was made on the second just preceding the squitter or in the previous second due to processing delays. A bit that specifies an even or odd GPS second is sufficient to resolve this ambiguity. Latitude and longitude are provided to a resolution of about 5 m with an ambiguity of about 360 nmi. Provision is made in the encoding to recover the full unambiguous position of an aircraft from the information provided by two consecutive position reports [9].

The surface-surveillance format is used to relay the positions of aircraft on the airport surface. Because greater resolutions are needed in the latitude and longitude information for surface-position messages, the two most significant bits in the latitude and longitude fields of the airborne-position format are replaced with two additional least significant bits to achieve a resolution of approximately 1.2 m with an ambiguity of 90 nmi. Because altitude information is not needed in surface-position messages, information on aircraft movement and track angle is provided instead.

Finally, the flight-identification format is used to relay the identity (ID) of an aircraft, e.g., AA 123 for American Airlines flight 123. This information is necessary to support CDTI. Because an aircraft's ID is fixed for the duration of a flight, the ID is provided in a separate format only once every 5 sec. Note that the position formats and the identification format of the GPS-Squitter all contain an aircraft's 24-bit Mode S address, as shown in Table 2, so that there is no problem in associating the position of an aircraft with its ID.

Occupancy of 1090-MHz Channel

One of the issues under study is the occupancy of the 1090-MHz channel. Table 3 shows a worst-case reply-rate scenario for a single Mode S transponder.

For a worst-case scenario, ATCRBS ground stations are assumed to interrogate the transponder at a rate of 100 interrogations/sec, with TCAS accounting for an additional 20 interrogations/sec. Because each ATCRBS reply takes 20.3 μsec, the 120 interrogations/sec results in a reply channel occupancy of 2436 μsec/sec. Mode S activity adds an additional 968 μsec, as shown in Table 3. For GPS-Squitter, the two 112-bit squitters/sec adds 240 μsec to the channel occupancy, and the one ID squitter per 5 sec adds an average of 24 μsec/sec. This total of 264 μsec/sec for the GPS-Squitter increases the total channel occupancy of the transponder from 0.340% to 0.367%—an increase that is considered tolerable.

It should be noted that the use of GPS-Squitter will enable TCAS and ATC surveillance systems to operate in a passive mode, thus eliminating the need for Mode S TCAS interrogations. As shown in Table 3, TCAS interrogations take up 320 μsec/sec of the channel occupancy. Consequently, GPS-Squitter will have the overall effect of *reducing* the occupancy of the reply channel by 320 – 264 = 56 μsec/sec.

The conclusion of this investigation is that squitter occupancy will not adversely affect current activities on the beacon channels and that overall channel occupancy will decrease when TCAS converts to the use of passive squitter reception for aircraft surveillance.

Air-Ground Operational Range

The design baseline for squitter-reception range was based on experience with TCAS. Table 4 presents antenna characteristics and a link budget for TCAS and GPS-Squitter receivers. Range improvements (relative to TCAS) for air surveillance from the ground were accomplished easily by improving the antenna gain through vertical aperture and by using horizontal sector beams. A second technique for enhancing the range performance was to use a receiver with a reduced noise figure. These improvements produced a

Table 3. Impact of GPS-Squitter on 1090-MHz Channel Occupancy[1]

	Transmissions	*Occupancy (μsec)*
ATCRBS		
Ground and TCAS	120	2436
Mode S		
Ground	1 short squitter	64
	3.8 long squitters	456
Squitter	1 short squitter	64
All-call	1 short squitter	64
TCAS	5 short squitters	320
Total		*968*
Total with current squitter		**3404**[2]
GPS-Squitter	2.2 long squitters	264
Total with GPS-Squitter		**3668**[3]

[1] The worst-case channel occupancy is calculated for one Mode S transponder during one second.
[2] Represents a channel occupancy of 0.340%.
[3] Represents a channel occupancy of 0.367%.

conservative GPS-Squitter operating range of 50 nmi for an omnidirectional antenna and 100 nmi for a six-sector antenna.

Airborne-Surveillance Capacity

Analysis Model. The technique used to estimate GPS-Squitter surveillance capacity [10] is based on the Poisson probability model for the reception of transponder transmissions. This technique is standard for estimating the probability of the arrival of randomly generated events in a listening time window.

Interference Mechanism. Mode S transponders transmit squitters at 1090 MHz. Because 1090 MHz is reserved principally for beacon radar use, the frequency is shared with activities of the current ATCRBS. Thus the interference events of interest are short (56 bit) and long (112 bit) Mode S replies, and ATCRBS replies. The lengths of the different types of replies are 64 μsec for 56-bit Mode S, 120 μsec for 112-bit Mode S, and 20.3 μsec for ATCRBS. Because the interference effect of an individual reply is a function of the length of the reply, the analysis must treat the effect of each reply separately.

Analysis Technique. The Poisson model is applied separately to each reply type to calculate the probability that an interfering reply will occur in the 120-μsec listening window needed to receive a squitter. To account for the 112-bit Mode S replies, the probability of receiving no replies in a window of 240 μsec is calculated. A window of 240 μsec is used because a squitter may not be received correctly if any part of the squitter is overlapped by a Mode S fruit reply, i.e., an interfering reply received from an interrogation by a neighboring sensor. Thus the window length is the sum of the lengths of the desired and interfering replies. The probability for the 56-bit case is calculated similarly except that a window of 184 μsec is used to account for the short Mode S reply. For the ATCRBS replies, the probability of receiving zero or one ATCRBS reply in a 140.3-μsec window is calculated. One ATCRBS reply is permitted in the listening window because Mode S has an error correction function that can correct for the effect of a single ATCRBS reply. The three individual probabilities are then multiplied to obtain the probability of successful squitter reception with the assumed fruit rate for each of the reply types.

Table 4. Antenna Characteristics and Link Budget for TCAS and GPS-Squitter Receivers

	TCAS receiver (10 nmi)	*GPS-Squitter 7-ft omnidirectional receiver (50 nmi)*	*GPS-Squitter six-element receiver (100 nmi)*
Transponder power, 250 W into antenna	54 dBm	54 dBm	54 dBm
Transponder antenna gain (horizontal direction)	0 dB	0 dB	0 dB
Free-space path loss	–118.5 dB	–132.5 dB	–138.5 dB
Receiving antenna gain (elevation angle of 0.5°)	0 dB	8 dB	14 dB
Receiving cable loss	–3 dB	–2 dB	–2 dB
Received power at receiver port	–67.5 dBm	–72.5 dBm	–72.5 dBm
Minimum power required for detection	–77 dBm	–82.5 dBm	–82.5 dBm
Nominal power margin	9.5 dB	10 dB	10 dB

Probability of 5-sec Update. The above analysis yields the probability of a successful reception of a squitter for each reception opportunity. Airborne GPS-Squitter transponders will generate squitters randomly once every 0.4 to 0.6 sec, leading to a total of at least 9 replies within the 5-sec update interval required for ATC surveillance. The probability that at least one of those replies will be received successfully in the 5-sec update interval can be calculated as one minus the probability of zero successful receptions out of 9 reply opportunities.

Airborne Fruit Model. Table 5 contains the reply rates assumed for each aircraft in the traffic model, and Table 6 presents a breakdown of the assumed origin of the replies for Case 1 of Table 5. Note that Case 1 is an extreme worst case that assumes the highest ground ATCRBS interrogation rate that was measured in high-density locations during development of Mode S and TCAS in 1978. Measured rates of this type always occurred in hot spots of tens of miles near airports and other congested areas. Case 1 assumes that the 120 ground ATCRBS replies/sec is the average rate for each aircraft within signal range of the ground receiver. For Mode S replies, the rates for all three cases also represent an extreme worst case, yielding 40 short and 30 long Mode S replies over a 5-sec scan period.

Types of Ground Stations. GPS-Squitter receiving stations will be of two types. The terminal configuration will use an omnidirectional antenna with a single receiver to provide a surveillance range of 50 nmi. The en route configuration will use a six-sector antenna with six receivers to provide a surveillance range of 100 nmi. In addition to providing more antenna gain for longer range, the six-sector antenna has the effect of reducing the reply rate seen by each receiver by a factor of 2.5 relative to the omnidirectional case because each of the six antennas receives replies from only a portion of the total aircraft population. The increase in operating density provided by the six-sector antenna may also be applied to the terminal

Table 5. Assumed Reply Rates for Three Different Traffic Models

Case	*ATCRBS*	*Mode S short squitters*	*Mode S long squitters*
	Replies per second transmitted from each aircraft		
1	120	8	6
2	60	8	6
3	0	8	6

Table 6. Details of Case 1 of Table 5

	ATCRBS	Mode S short	Mode S long
Ground	100	2	3.8
Squitter	0	1	2.2
TCAS	20	5	0
Total	*120*	*8*	*6*

configuration, as required, to handle high-density environments.

Airborne Operating Density. For the three cases of Table 5, Figure 4 presents the six-sector detection probability for each 0.5 sec. Figure 5 shows the effect of multiple squitter opportunities on the probability of receiving at least one reply successfully. The multiple-squitter effect of Figure 5 can be combined with the 0.5-sec performance of Figure 4 to produce the 5-sec detection probability in Figure 6. The point where each curve of Figure 6 crosses the 0.995 value defines the maximum GPS-Squitter operating density for that case. The results of this analysis are shown in Table 7, which also contains the results for the omnidirectional case. In an independent investigation of GPS-Squitter airborne capacity [11], a detailed simulation showed that the results obtained by the above analysis are conservative in that they underestimate the capacity by 7% to 30%, depending on the ATCRBS reply rate.

Interpretation of Density Results. The performance summarized in Table 7 is conservative in that worst-case values are used for the ATCRBS interrogation rate for Case 1, and worst-case Mode S reply rates are used for all of the cases. In addition, the results are conservative because the analysis does not take into account the fact that *dynamic thresholding* [12] and *pulse-position modulation* [13] can be used to make Mode S reply reception tolerant to interfering replies that are of lower signal strength than the desired squitter. Dynamic thresholding derived from the squitter preamble is used to limit the effect of lower-strength fruit replies. Pulse-position modulation is a coding technique in which the bit value is determined

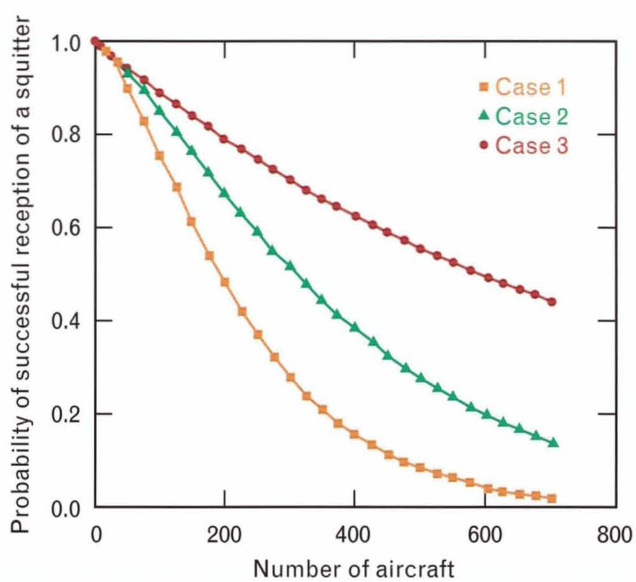


FIGURE 4. Surveillance of airborne aircraft: squitter-reception probability for the three cases of Table 5. The probabilities are for a six-sector antenna over a time period of 0.5 sec.

from the position of a 0.5-μsec pulse in the leading or trailing half of a 1-μsec window. The bit value is declared by sampling the amplitude of the leading and trailing pulse positions and assigning the value based on the sample with the higher amplitude. The analysis assumes the worst case in that any reply within line of sight of the ground receiver out to maximum listening range (150 nmi for the omnidirectional antenna and 250 nmi for the six-sector antenna) could interfere with the reception of a squitter. Thus the reply probability over 5 sec applies to an aircraft at maximum operational range (50 nmi for the omnidirectional and 100 nmi for the six-sector antenna). The probability of a successful reply will increase as the aircraft range to the ground receiver decreases. This increase in reply probability means that the average time between successful replies will also decrease as the range to the receiving station decreases. Thus the reception of replies will be at a higher update rate than the 5 sec used in the analysis.

Operation in Higher-Density Environments. The capacity analysis indicates that the GPS-Squitter concept has more than adequate capacity to operate in moderate-to-low-density traffic environments—the intended operational environments for the system's potential initial implementation. If required in the

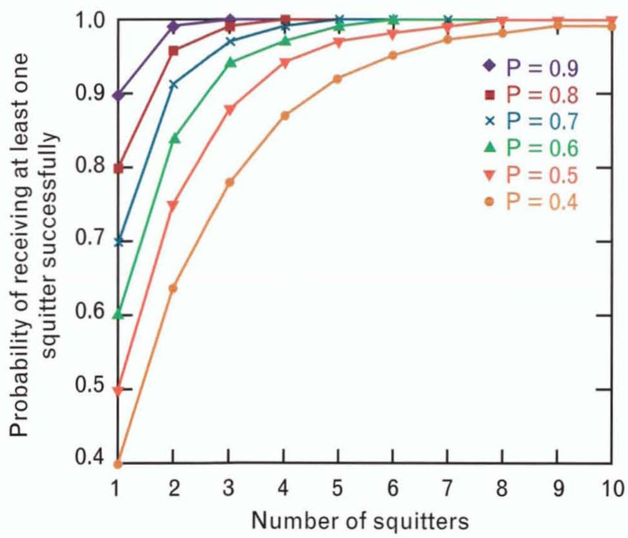


FIGURE 5. Surveillance of airborne aircraft: the effect of multiple squitter opportunities (trials) on the probability of receiving at least one reply successfully. The six curves represent different probabilities, from 0.4 to 0.9.

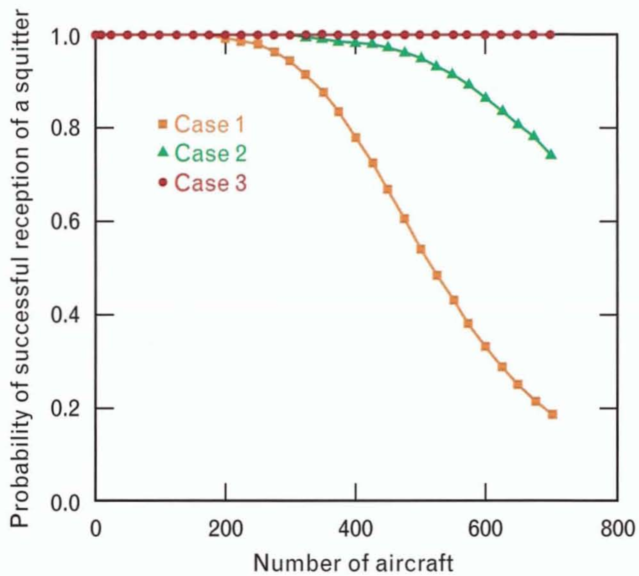


FIGURE 6. Surveillance of airborne aircraft: squitter-reception probability for the three cases of Table 5. The probabilities are for a six-sector antenna over a time period of 5 sec.

future, operation in higher-density environments can be obtained by using antennas with an increased number of sectors. Table 7 indicates the capacity increase that can be achieved with antennas of nine and twelve sectors.

Capability of Random Squitter. The above analysis provides an interesting perspective on the ability of the GPS-Squitter concept, which uses random squitters, to satisfy aviation surveillance requirements. The TCAS surveillance requirement is for a 1-sec update rate out to 14 nmi; terminal ATC operation requires a 5-sec update for aircraft out to 60 nmi; and en route sensors currently provide a 12-sec update rate to a range of 200 nmi. Because a TCAS GPS-Squitter receiver would operate at a sensitivity level adequate for 14 nmi, the receiver would process squitters from only a small fraction of the aircraft that are visible to a terminal or en route squitter receiver. The 14-nmi sensitivity level permits TCAS to operate at a squitter probability level suitable for a 1-sec update. Because the terminal and en route receivers have a greater operating range, they must handle a much higher signal traffic density. The higher density leads to a lower probability of reception of a single squitter, but the multiple squitter opportunities produce a high probability of an update during the

Table 7. Maximum Number of Aircraft That Can Be Handled by Different Antennas for the Three Cases of Table 5

Case	*Omnidirectional*[1]	*Six-sector*[2]	*Nine-sector*	*Twelve-sector*
1	85	215	325	425
2	140	350	525	700
3	280	700	1050	1400

[1] For radius of 150 nmi
[2] For radius of 250 nmi

5- or 12-sec update period. Thus both surveillance requirements (for TCAS as well as for terminal and en route receivers) can be handled simultaneously by the same random squitter.

Surface-Surveillance Capacity

The same model and interference mechanism used for airborne surveillance capacity is used for the surface case.

Analysis Technique. For the surface case, the principal interference is the long squitters generated by other surface aircraft.

Probability of a 1.0-sec Update. A GPS-Squitter transponder on the airport surface will transmit an average of two squitters/sec. The probability of receiving at least one of those squitters each second is calculated as one minus the probability of zero successful receptions out of two reply opportunities.

Surface Fruit Model. To limit surface squitters from interfering with one another, two ADS squitter rates are used depending on aircraft motion. If an aircraft is moving, it will transmit surveillance squitters at the two-per-second rate. If the aircraft is stationary, the squitter rate drops to one squitter every 5 sec. The rate returns to two per second immediately when the aircraft begins to move. Provision has also been made for the ground system to command an aircraft to remain at the higher rate, independent of aircraft motion, for cases requiring the continued high-rate monitoring of a stationary aircraft, e.g., when an aircraft is stopped on a taxiway at an intersection of an active runway.

No other surveillance replies can be elicited from surface aircraft because GPS-Squitter transponders on the surface do not respond to ATCRBS or Mode S all-call interrogations. Additionally, the short squitter (retained for compatibility with current TCAS equipment) will not be generated by GPS-Squitter transponders while on the surface.

Fruit replies from airborne aircraft are a minor factor in calculating surface capacity. As discussed earlier, the Mode S 1090-MHz waveform uses pulse-position modulation that is tolerant of lower-level interference. With pulse-position modulation, replies can normally be decoded successfully if interfering replies are at least 3 dB below the desired signal. To allow for transponder power variations and propagation anomalies, a margin of 10 dB is used in the analysis. Thus, because the operating range on the surface is very short (nominally less than 2 nmi), replies from aircraft beyond about 6 nmi are assumed not to affect surface performance. In addition, the antennas used for reception of surface squitters will have vertical aperture to discriminate against replies from close-range high-elevation airborne aircraft. The combination of the tolerance of the Mode S squitter to lower-level interference and the vertical antenna pattern minimizes the effects of transmissions from airborne aircraft on the performance of surface operation.

Surface Operating Density. In addition to interference from fruit replies, reception on the airport surface must take into account the effects of multipath. Surface measurements made at Boston's Logan International Airport indicate that a single omnidirectional receiving station will achieve a probability of reception of greater than 95% when there is no blockage of the signal and no interfering fruit replies in the listening window. Thus the 0.5-sec reply probability will include a factor of 0.95 to account conservatively for the effects of multipath.

An additional effect that must be included is the reply loss due to airborne aircraft that are within range of the surface receiving stations. Analysis of current surveillance data indicates that an interference source for each surface receiver would be the equivalent of one airborne aircraft. A worst case of 20 Case 2 airborne aircraft (as defined in Table 5) is assumed in the following analysis of surface operating density.

Figure 7 presents the results of performing a worst-case capacity calculation for a 0.5-sec update with a fixed squitter rate of 2.2 squitters/sec (all aircraft moving), and Figure 8 presents the results for a time period of 1 sec. A summary of surface operating performance is given in Table 8 together with an estimate of the effect of the variable squitter rate on surface capacity. Table 8 assumes that the maximum surface squitter rate with the variable rate technique is no greater than 220 squitters/sec—a rate that would be produced by 100 moving aircraft. This assumption is conservative because the peak traffic count in the movement area of the largest terminals in the U.S. is about 100 aircraft. This peak is reached during delay conditions in which the majority of the aircraft are stationary as a result of, for example, inclement weather.

Data-Link Capacity

The principal use of GPS-Squitter for air surveillance is as a replacement for a conventional Mode S sensor in moderate-to-low-density airspace, i.e., in areas not covered by the Mode S sensors currently being implemented. To provide the same service as a Mode S sensor, the GPS-Squitter station must also provide a two-way data link. This link can be readily accomplished because the surveillance function of these stations requires the ability to transmit on 1030 MHz (for DGPS broadcast) and to receive on 1090 MHz (for squitter reception). Thus the provision of a two-way data link requires only the addition of a modest data-link interface and protocol control function in the GPS-Squitter ground station. The capacity of the two-way data-link capability is defined by the following considerations.

Self-Interference Limit. The station will not be able to receive squitters while it is transmitting on 1030 MHz or while it is receiving elicited replies on 1090 MHz. Thus the interrogation rate must be kept low.

Transponder Occupancy Limit. Each Mode S interrogation occupies ATCRBS transponders for 35 μsec and Mode S transponders (other than the addressed transponder) for 45 μsec. The GPS-Squitter stations use omnidirectional or sector-beam antennas to transmit Mode S interrogations, as opposed to the narrow-beam (2.4°) antennas used by Mode S sensors. Thus each Mode S interrogation from a GPS-Squitter station will affect aircraft over a larger region than the same interrogation transmitted with a Mode S sensor. This factor leads to the conclusions that (1) the GPS-Squitter interrogation rate must be kept low and (2) GPS-Squitter data-link activity must be avoided in high-density environments where transponder occupancy is a concern. The second condition is met easily because Mode S sensors are already being provided for data-link use in high-density environments.

Maximum Link Utilization. As with TCAS, the ap-

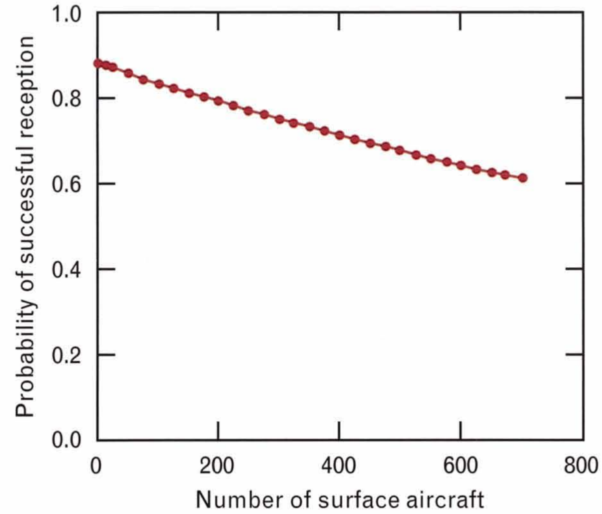


FIGURE 7. Surveillance of aircraft on the airport surface: squitter-reception probability each 0.5 sec.

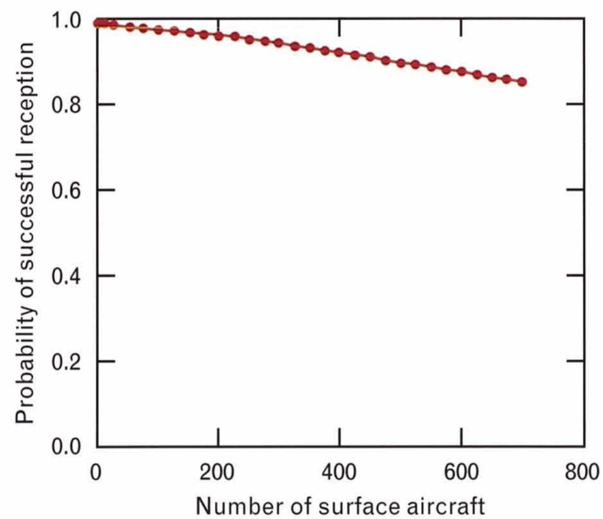


FIGURE 8. Surveillance of aircraft on the airport surface: squitter-reception probability for a time period of 1 sec.

Table 8. Surface Operating Performance[1]

Squitter rate used	*Number of aircraft on airport surface*	*System reliability*
Fixed	250	95%
	500	90%
Variable	500	97%

[1] Data are for an update time of 1 sec, multipath factor of 95%, and 20 airborne aircraft per receiver.

proach used to achieve these requirements is to limit GPS-Squitter two-way data-link activity to a 1% occupancy per second of Mode S and ATCRBS transponders. Note that, as with TCAS, this 1% is a maximum that can be generated by all of the GPS-Squitter data-link activity in a region of airspace. In areas where GPS-Squitter stations have overlapping coverage, the joint transponder occupancy caused by all stations must be kept to no more than 1%. As GPS-Squitter is implemented, the active TCAS interrogation rate will decrease because TCAS will be able to provide surveillance of nearby aircraft by passively listening to the ADS squitters. Eventually, TCAS will become almost completely passive. At that point, GPS-Squitter stations may be allowed to increase their activity to 2% to take advantage of the decrease in TCAS link activity.

As mentioned earlier, a Mode S interrogation occupies an ATCRBS transponder for 35 μsec and a Mode S transponder for 45 μsec. The longer occupancy time of the Mode S transponder is used to define the allowable interrogation rate. A 1% utilization of a Mode S transponder is equal to 10 msec over a 1-sec period. Thus the maximum interrogation rate is equal to 10 msec/sec divided by 45 μsec, or 220 interrogations/sec. A 2% limit would yield a maximum interrogation rate of 440 interrogations/sec.

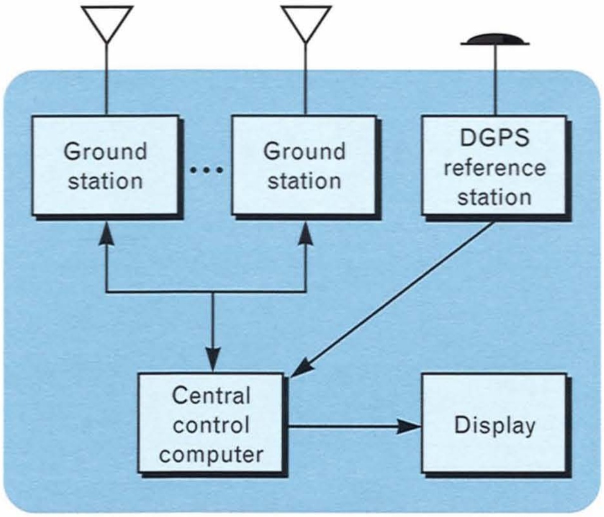
If a six-sector antenna is used, a higher data rate can be supported because each interrogation will occupy only those aircraft which are covered by the beam used for the interrogation. The surveillance benefit of a six-sector antenna compared with an omnidirectional antenna has been estimated to be equivalent to a traffic reduction of 2.5 (see the sub-subsection "Types of Ground Stations" on p. 279). This reduction results from the division of the traffic population among the six beams, and takes into account traffic bunching and antenna sidelobe effects. These considerations are the same ones that would be used to determine the effective occupancy of Mode S transponders in the coverage area of a GPS-Squitter station transmitting over a six-sector antenna. Therefore, the maximum rates calculated for the omnidirectional antenna case can be increased by a factor of 2.5 for the six-sector antenna case. This increase yields rates of 550 and 1100 interrogations/sec for the 1% and 2% limits, respectively.

Table 9. Summary of GPS-Squitter Data-Link Capacity

	Interference budget 1%	2%
Omnidirectional antenna (capacity per station in kb/sec)		
Number of stations		
1	22.5	45
2	11.3	22.5
3	7.5	15
4	5.6	11.3
Total	22.5	45
Six-sector antenna (capacity per station in kb/sec)		
Number of stations		
1	22.5	45
2	22.5	45
3	18.7	37.3
4	14	28
Total	56	112

A summary of the data-link capacities per ground station corresponding to the interrogation rate limits determined above is presented in Table 9. The table includes data for one through four ground stations for nominal data-link operating characteristics. Note that a single six-sector antenna station cannot exceed the omnidirectional interrogation limit even if the station has no overlapping coverage with neighboring stations. This limit has been imposed to ensure that a Mode S transponder close to the station is not occupied by more than the occupancy limit because of the reception of interrogations from the sidelobes of the sector antennas. These estimates indicate that GPS-Squitter ground stations can provide useful data-link capacity in regions not served by the high-capacity Mode S narrow-beam interrogators (each of which has a data-link capacity of approximately 100 kb/sec of user data).

The stationary omnidirectional and sector-beam antennas used for GPS-Squitter stations can provide immediate aircraft data-link access. In this respect, these antennas offer the same access-time perfor-



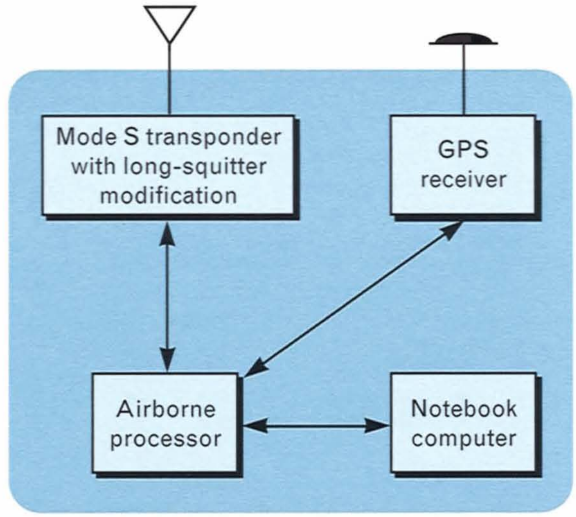


FIGURE 9. Equipment used in the field testing of GPS-Squitter: (a) ground equipment and (b) avionics.

mance as an electronically scanned antenna. Some limited use of the GPS-Squitter stations might be desirable in high-density airspace to take advantage of this response time for applications that cannot be served by a scanning beam antenna. Such usage of the GPS-Squitter data link is possible if the interrogations are kept to a low rate. For additional capacity beyond the capability of the omnidirectional and six-sector beam antennas, an antenna with a greater number of sectors or a data-link-only electronically scanned antenna can be used.

Field Test Program

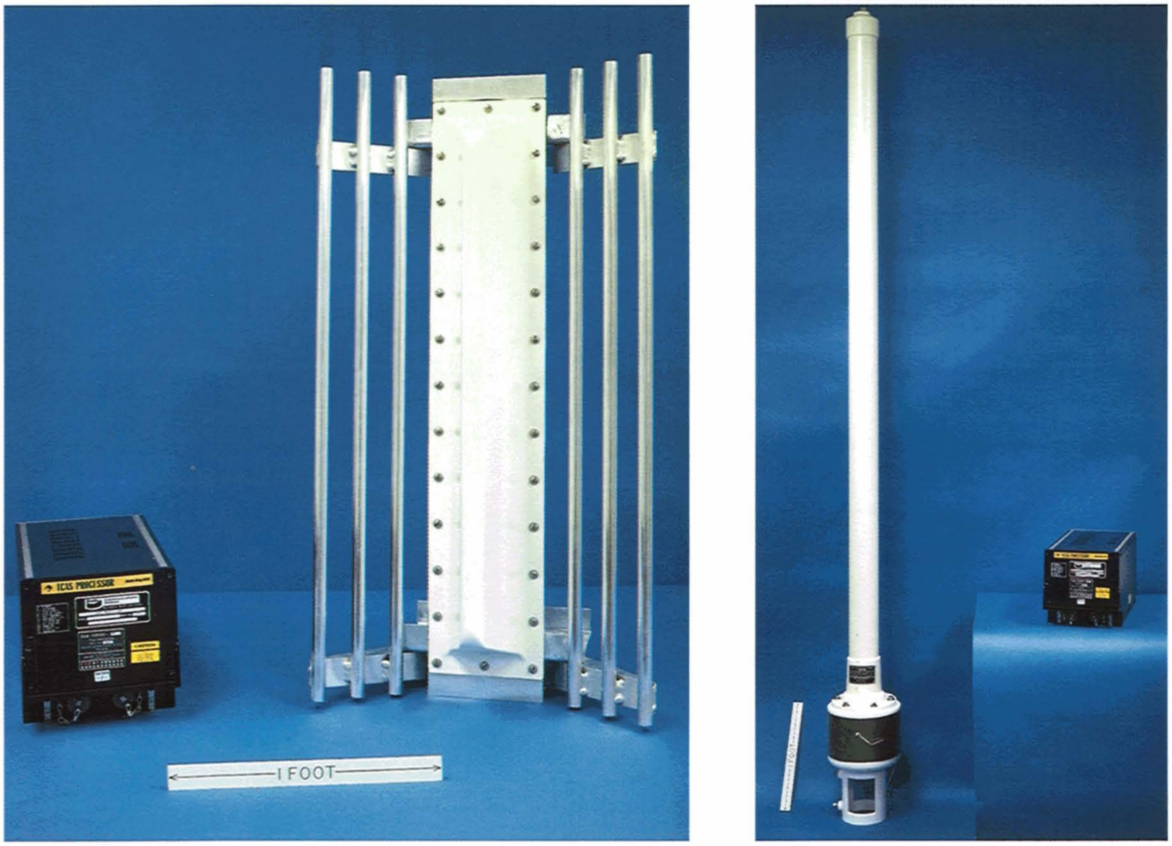
Initial field testing of the GPS-Squitter concept has been performed. A proof-of-concept evaluation was conducted at Hanscom Field in Bedford, Massachusetts, during the summer and fall of 1993, and an operational suitability assessment was initiated at Boston's Logan International Airport in early 1994. This section describes the GPS-Squitter system configuration for these experiments and the following two sections discuss the results of the Hanscom Field and Logan Airport experiments.

Ground Equipment

The equipment used during the field testing of GPS-Squitter is shown in Figure 9. The ground equipment included a DGPS reference station, transmit/receive ground stations, and a central control computer and display system.

DGPS Reference Station. The reference station used was a Trimble Model 4000RL. The horizontal position accuracy that can be obtained with GPS is reported to be within 100 m at least 95% of the time [14], which is sufficient for most airborne applications. Surface surveillance, however, requires greater accuracy. During the surface testing of GPS-Squitter, differential GPS (DGPS) techniques were utilized for improved accuracy.

Ground Stations. The GPS-Squitter ground stations served two basic purposes during the field testing: they received the long squitters emitted by the test vehicles and they transmitted DGPS corrections to the vehicles. For the Hanscom Field tests, Lincoln Laboratory assembled two ground stations, each of which was connected to a simple antenna with an omnidirectional pattern in azimuth. For the experiments at Logan Airport, four ground stations known as Ground Interrogator Receiver Units (GIRU) were obtained from Allied-Signal Air Transport Avionics. The GIRUs were TCAS II processors with minor modifications to the radio frequency (RF) hardware and to the software. Two types of antennas were installed with the GIRUs at Logan Airport. The first type was the variable wing antenna (Figure 10[a]), which is based on antennas used by cellular telephone companies. The variable wing antenna has an azimuth beamwidth that is adjustable between 60° and



(a) (b)

FIGURE 10. The two types of antennas used in field tests at Boston's Logan International Airport: (a) variable wing antenna, and (b) Distance Measuring Equipment (DME) antenna. The antennas were installed with ground stations known as Ground Interrogator Receiver Units (GIRU).

140°; the 140° setting was used at Logan Airport. The second type of antenna used was the FAA's Distance Measuring Equipment (DME) antenna (Figure 10[b]). The DME antenna has an omnidirectional beam in azimuth.

Central Control Computer. A Sun Sparc10 workstation served as the central control computer, where the following tasks were performed: (1) receive the DGPS corrections from the reference station and reformat them for transmission by the ground stations, (2) decode the long squitters received by the ground stations, (3) act as the primary data recording device, and (4) provide real-time target display.

Avionics

Three test vehicles were equipped with GPS-Squitter avionics for the field experiments. Two of the vehicles—a Cessna 172 and a truck—were used at Hanscom Field, and a Cessna 421 was added later for the Logan Airport experiments. The test vehicles were equipped with the following avionics: a Mode S transponder modified for GPS-Squitter, a GPS receiver, and an airborne processor and notebook computer.

GPS-Squitter Transponder. Mode S transponders were obtained from the Collins Division of Rockwell International and modified to transmit GPS-Squitter messages. Only a minor software modification to these transponders was required to provide them with long-squitter capability.

GPS Receiver. Each test vehicle was equipped with a Trimble 2100 GPS receiver capable of processing DGPS correction messages. Information available from the receiver at a 1-Hz rate included GPS time, latitude, longitude, barometric altitude, speed, and heading.

Airborne Processor and Notebook Computer. In addition to a modified transponder and a GPS receiver, each of the test vehicles was outfitted with an airborne processor and a notebook computer. The Lincoln Laboratory–developed airborne processor served as the interface between the GPS receiver and the GPS-Squitter transponder. The notebook computer was used for on-board data recording.

Hanscom Field Results

The GPS-Squitter concept was first tested at Hanscom Field in a series of experiments known as the proof-of-concept evaluation [15]. The primary objective of the Hanscom Field testing was to demonstrate the feasibility of using long squitters to downlink ADS information. Other objectives included (1) evaluating the reliability of the 1030/1090-MHz data link on an airport surface, (2) determining surface-surveillance performance for the two-ground-station system, and (3) demonstrating air surveillance with a simple ground-station antenna.

Surface Surveillance

Because the GPS-Squitter concept is based on the use of Mode S waveforms, the system's performance in air-to-ground and air-to-air applications was well understood from past experience with Mode S. What was not as clear, however, was how well the long squitter would work on the airport surface where blockage from buildings or multipath reflections might prevent a transmission from being decoded correctly. Thus the initial testing at Hanscom Field focused on surface surveillance.

An example of the surface-surveillance performance is shown in Figure 11. During the test, the surface vehicle (a truck) transmitted squitters while driving along the perimeter of Hanscom Field, and the squitters were received by two ground stations. Once-per-second updates were received 96% of the time by one of the ground stations and 93% of the time by the other station, resulting in a combined coverage of 99.6%. Additional surface testing at Hanscom Field with the truck and the Cessna 172 showed similar results. Blockage from the control tower and multipath interference occasionally affected the ground stations but rarely did these problems affect both ground stations simultaneously. Reference 16 provides a complete description of these surface-surveillance results.

Air Surveillance

A long-range airborne test was performed with the Cessna 172 and one of the ground stations at Hanscom Field. For this test, the ground station was connected to a DME antenna similar to the one shown in Figure 10(b). System studies had predicted that the DME antenna would be sufficient to provide air surveillance in the terminal area out to a range of 50 nmi with a 10-dB margin [17].

The flight path taken by the Cessna 172 is shown in Figure 12. The Cessna 172 flew to the northwest of Hanscom Field out to a maximum range of 110 nmi at an altitude of 10,000 ft, and returned in a southeast direction at an altitude of 9000 ft. In Figure 12, three types of symbols are used to indicate long squitters that were received during the flight: blue dots for squitters that were received within 3 sec of the previous squitter, i.e., an update time less than or equal to

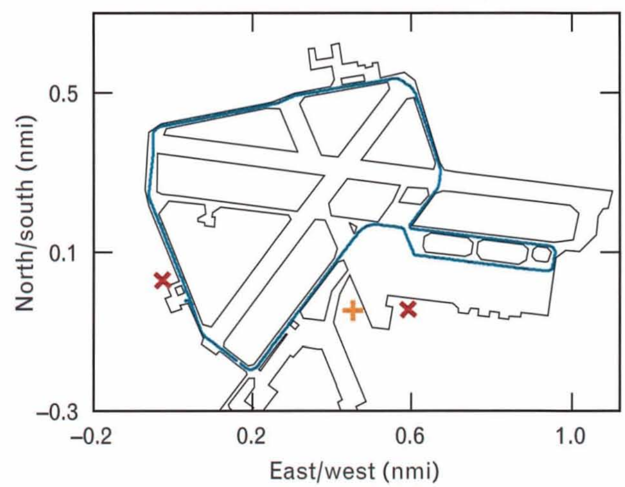


FIGURE 11. Surface-surveillance squitter-reception performance at Hanscom Field, Bedford, Massachusetts. During the field test, a truck transmitted squitters while driving along the perimeter of Hanscom Field, and the squitters were received by two ground stations. The truck route is shown in blue, the ground stations are represented by red Xs, and a control tower is indicated with a yellow +. Despite blockage from the control tower and multipath interference, once-per-second updates were received 96% of the time by one of the ground stations and 93% of the time by the other station, resulting in a combined coverage of 99.6%.

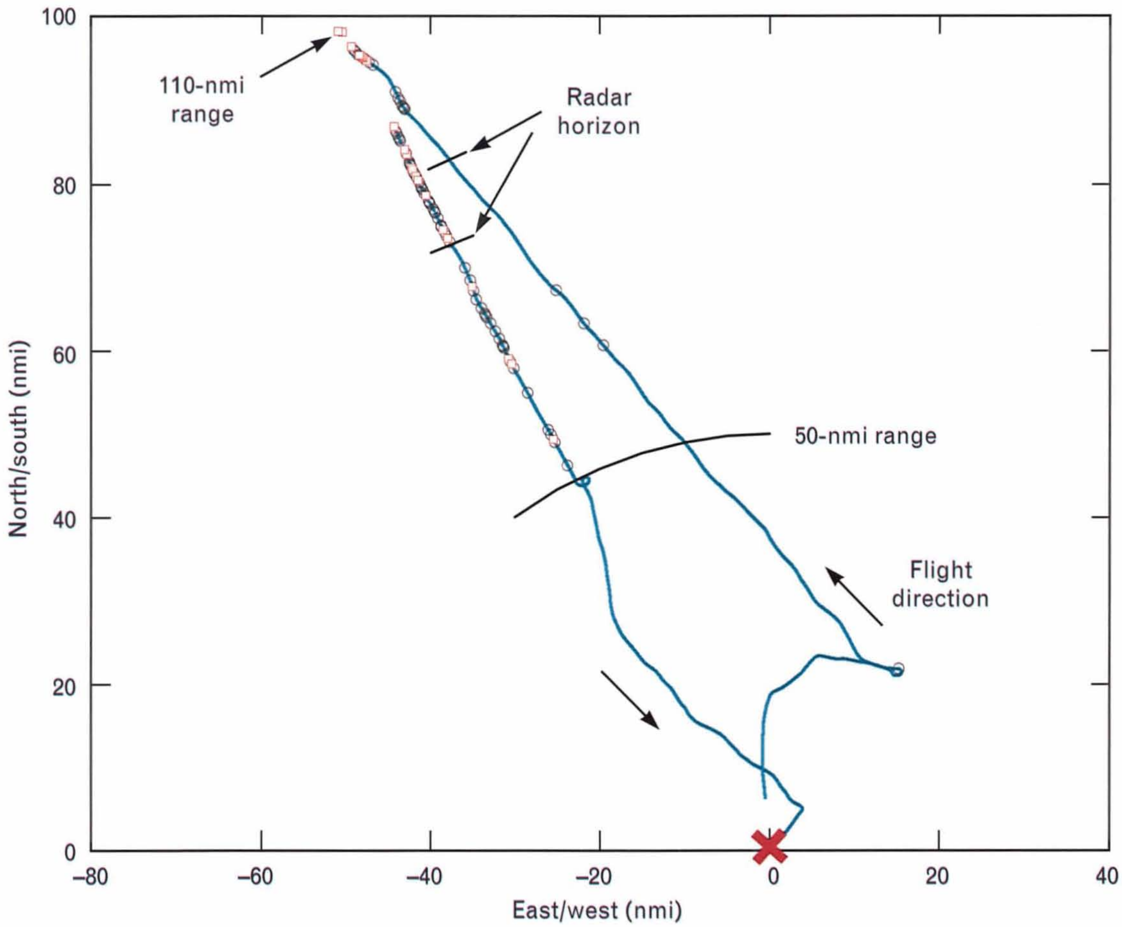


FIGURE 12. Air-surveillance squitter-reception performance at Hanscom Field. During the test, a Cessna 172 flew northwest to a range of 110 nmi and then turned around and headed back to Hanscom Field. During the flight, the aircraft transmitted squitters continuously, and the squitters were received by a ground station. In the figure, a red X indicates the location of the ground station, and three types of symbols are used to indicate long squitters that were received during the flight. Blue dots indicate squitters that were received within 3 sec of the previous squitter, i.e., an update time less than or equal to 3 sec; an open black circle indicates an update time between 3 and 5 sec; and a red square indicates an update time greater than 5 sec. The probability that a squitter would be received within 5 sec was 100% for a range up to 50 nmi, 99.6% for ranges up to 70 nmi, and 99.3% for ranges up to 90 nmi. A lower flight altitude and the rear-mounted aircraft antenna resulted in somewhat lower performance on the return flight.

3 sec; an open black circle for an update time between 3 and 5 sec; and a red square for an update time greater than 5 sec.

For air surveillance in terminal areas, radars with scanning beam antennas are currently used to obtain an update time of about 5 sec. Within 50 nmi of Hanscom Field, such performance was achieved 100% of the time. In fact, within this range, updates were obtained every 3 sec or less with only one exception. The performance beyond 50 nmi was also very good out to the radar horizon.

Logan International Airport Results

The testing at Hanscom Field showed that a GPS-Squitter system with two ground stations can provide very good surface surveillance at a relatively small airport. The primary interest in surface surveillance, however, is at the busiest airports. Thus the Hanscom Field experiments were followed by an operational suitability assessment at Logan Airport. Testing at Logan Airport centered on the surface-surveillance application, and individual experiments were performed to assess (1) coverage in the movement area, including the runways and taxiways, (2) coverage in the gate area, (3) dynamic coverage, and (4) the difference in performance between bottom-mounted and top-mounted transponder antennas. In addition, the air surveillance of the system was also investigated for a flight of the Cessna 421.

Coverage of Movement Area

Two tests were conducted at Logan Airport in the early morning to determine the surveillance coverage in the aircraft movement area, including runways and taxiways. The first test was conducted on 4 February and the second on 30 June 1994. During the tests, a truck transmitted squitters while traversing nearly every portion of the aircraft movement area, as shown in Figure 13. The squitters were received by four GIRU ground stations. Three of the ground stations were placed on buildings on one side of the airfield, and these three stations all used directional antennas similar to the antenna shown in Figure 10(a). The fourth ground station was housed in a van and deployed on the field. This station used the omnidirectional DME antenna (Figure 10[b]).

The surveillance coverage was excellent during both tests. On 4 February, once-per-second surveillance updates were obtained of the truck by at least one of the four ground stations 99.6% of the time. On 30 June, once-per-second updates were received 99.9% of the time.

Coverage of Gate Area

The GIRUs were deployed at Logan Airport to provide good surveillance of the movement areas; i.e., coverage of the gate areas was not a consideration in choosing the GIRU locations. Nevertheless, there was interest in assessing the gate-area coverage because of the possibility that the ground stations could provide data-link services to surface aircraft. Thus, on 30 June the truck was taxied throughout the gate area, as shown in Figure 14. As expected, the surveillance of the gate areas was below that of the movement area, but the gate-area coverage was still quite good: once-per-second updates were received 85.9% of the time. This percentage represents the success of only the 1090-MHz downlink frequency. Two-way data-link services would also require the 1030-MHz uplink channel. The performance at 1030 MHz was not assessed but is anticipated to be similar to the 1090-MHz performance.

Dynamic Coverage

Dynamic coverage refers to surveillance as affected by dynamic, i.e., moving, objects such as other aircraft and vehicles. Of particular concern are cases in which the aircraft of interest is in the midst of other moving aircraft that might either block the desired squitter or serve as sources of multipath reflections that garble the squitter. Three observations of dynamic coverage were made of different vehicles: a commercial aircraft, the Cessna 172, and the Cessna 421.

In November 1993, when only the GIRU at the

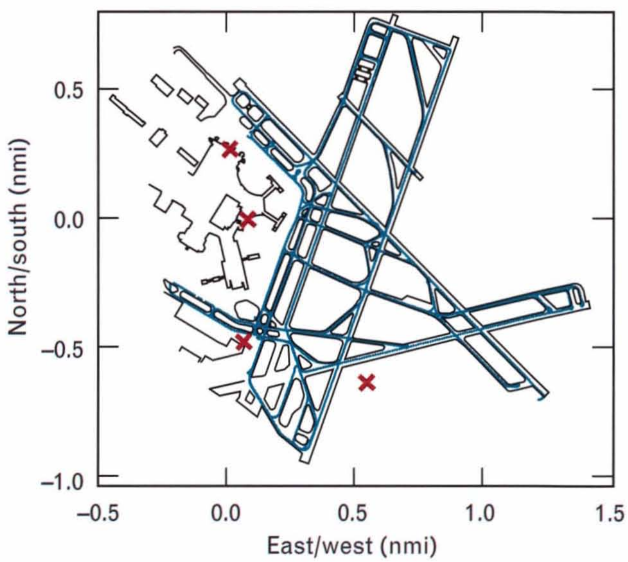


FIGURE 13. Surface-surveillance squitter-reception performance at Boston's Logan International Airport. During the test, a truck transmitted squitters while traveling along the airport runways and taxiways, and the squitters were received by four ground stations. The locations of the ground stations are shown with red Xs, and the truck route for a test conducted on 30 June 1994 is shown in blue. During the test, once-per-second position updates were obtained from the truck by at least one of the four ground stations 99.9% of the time. (Note: A similar test was conducted on 4 February 1994. During that test, once-per-second updates were received 99.6% of the time.)

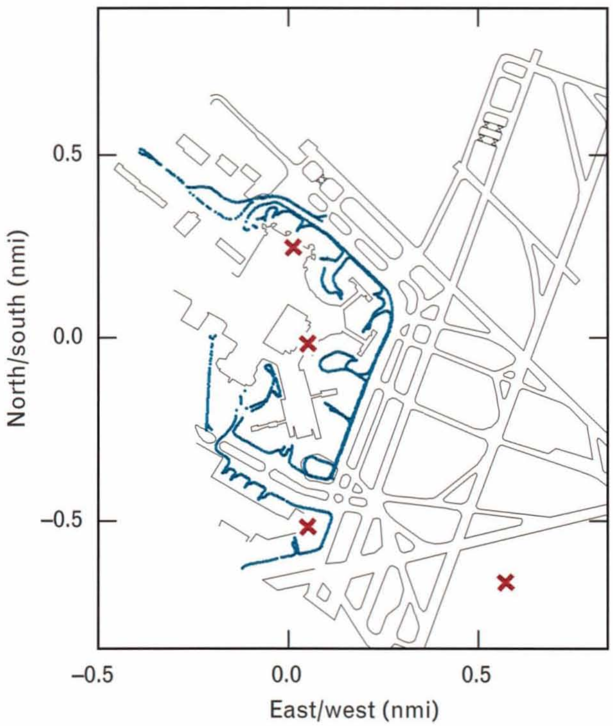


FIGURE 14. Surface-surveillance squitter-reception performance for the gate areas of Logan Airport. This test was similar to the test of Figure 13, except the truck traveled throughout the gate areas. The truck path is again shown in blue. Although the surveillance performance for the gate areas was below that for the runways and taxiways, the gate-area coverage was still quite good: once-per-second updates were received 85.9% of the time.

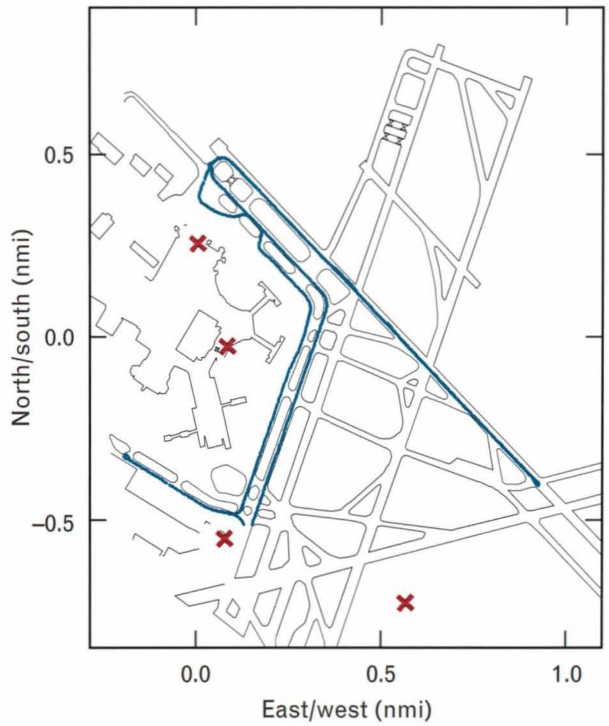


FIGURE 15. Comparison of top-mounted aircraft antenna with bottom-mounted antenna. During the test, the Cessna 172 taxied along a route (shown in blue) while using its top antenna to transmit squitters and then repeated the same route while using its bottom antenna. The performance for the top and bottom antennas was remarkably similar. With the top antenna, once-per-second position updates were received 98.6% of the time; with the bottom antenna the figure was 98.4%.

top of Figure 13 was operational, a Midwest Express aircraft was observed taxiing in preparation for takeoff. The aircraft was equipped with TCAS and the vehicle happened to be emitting short squitters once per second while taxiing. This relatively small aircraft was in line with other larger aircraft, which frequently obscured the small aircraft visually from the vantage point of the GIRU antenna. In addition, the larger aircraft were possible sources of multipath reflections. Nevertheless, analysis of the GIRU recorded data showed that the squitters from the Midwest Express aircraft were received quite reliably, with only occasional misses. In fact, the largest number of consecutive misses was three, and this condition occurred only once. These results were considered promising because, by extrapolation, the data suggested a high probability of receiving at least one squitter per second with four GIRUs operational and with a transmission rate of two squitters per second.

In February 1994 in a test using all four GIRUs, the Cessna 172 taxied three times within 100 ft of other larger aircraft. In each instance the larger aircraft blocked the signal path to one of the GIRUs and served as possible sources of multipath to the other three ground stations. In spite of the interference and multipath effects, at least one GIRU received a long squitter from the Cessna 172 during each second of the surveillance.

Later that same day, the Cessna 421 joined a line of larger taxiing aircraft on the outer taxiway in preparation for takeoff. In addition to the taxiing aircraft, there were other large aircraft within 1000 ft of the Cessna 421. Still, as with the Cessna 172 earlier, at least one GIRU received a long squitter

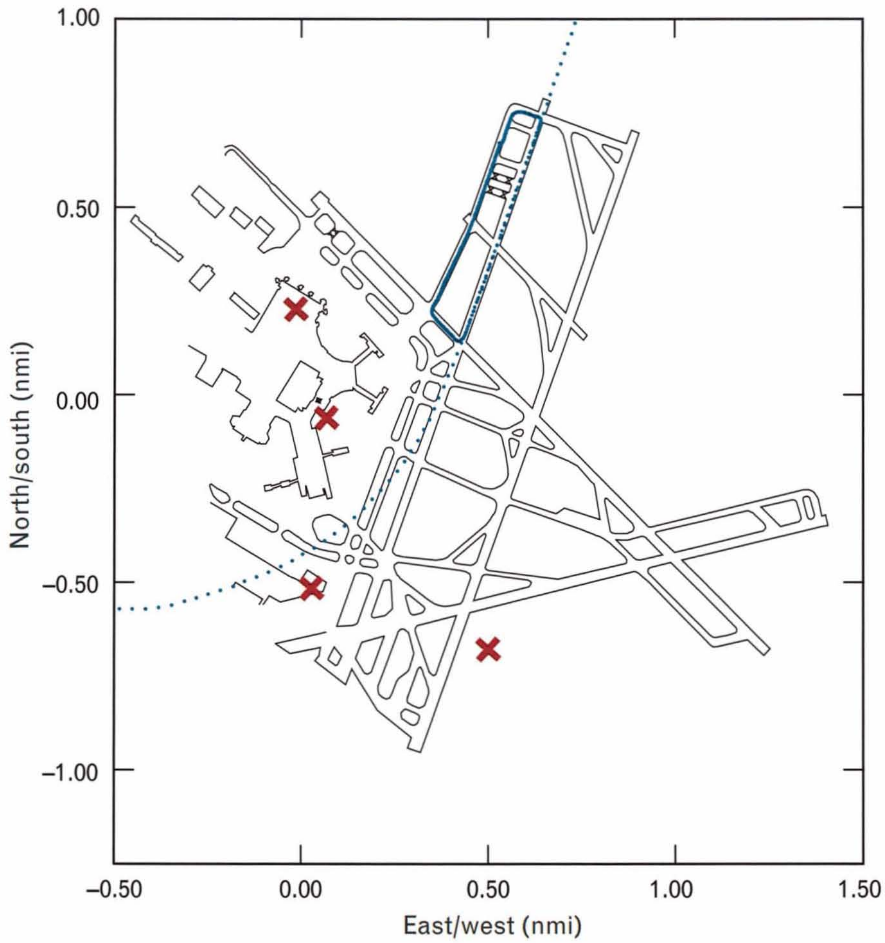


FIGURE 16. Air-surveillance performance at Logan Airport for a flight of the Cessna 421 from approach to departure on 17 February 1994. The red X symbols indicate the locations of the four ground stations, and the blue dots represent the locations of the Cessna 421 at different points in time; i.e., closer dot spacings indicate slower speeds; farther spacings indicate higher speeds. The aircraft flies in from the north, lands on the runway, moves along the runway and taxiways in a clockwise direction, takes flight again, and departs from the airport in a southwest direction. For the entire test the overall probability of one of the four ground stations receiving a once-per-second update was 100%, including the time the aircraft was in a line of traffic waiting to take off.

from the Cessna 421 during each second of the surveillance measurements.

Coverage of Top versus Bottom Antenna

The Cessna 172 that was used in the GPS-Squitter testing has both top-mounted and bottom-mounted Mode S transponder antennas. During most of the testing, the aircraft radiated squitters by alternating between the two antennas while airborne and using only the top antenna while on the airport surface. This mode of operation was expected to provide the best performance. Although it is common for commercial aircraft to have both top and bottom antennas, general aviation aircraft typically have only a bottom-mounted one. For this reason, a surface test was conducted to compare the performance of the bottom antenna with that of the top antenna. During the test, the Cessna 172 taxied along a route while using its top antenna to transmit squitters and then repeated the same route while using its bottom antenna. Because the testing was conducted during the day, the route had to be restricted so that the test would not interfere with regular airport operations. The test route, as shown in Figure 15, contained one of the runways as well as the inner and outer taxiways near the terminal buildings. This route represented the most demanding portion of the surface coverage area. The performance for the top and bottom antennas was remarkably similar. With the top antenna, once-per-second position updates were received 98.6% of the time; with the bottom antenna the figure was 98.4%. The successful operation with the bottom antenna was a result of three of the receiving stations using antennas that were 50 to 100 ft above the ground surface, thus minimizing the effect of ground multipath degradation on replies received from the bottom antenna.

Air Surveillance

An airborne test was performed at Logan Airport with the Cessna 421 and the four ground stations on 17 February 1994. During the test, the Cessna 421 flew into the airport from the north, landed on a runway, circled the runway, took flight again, and departed from the airport in a southwest direction, as shown in Figure 16 on the previous page. During this time, the overall probability of one of the four ground stations receiving a once-per-second update from the aircraft was 100% for the entire flight out to a range of 10 nmi, including the time the aircraft was in a line of traffic waiting to take off.

Summary

GPS-Squitter has the capability to provide significant benefits to the National Airspace System:

- GPS-Squitter is a systems approach that supports automatic dependent surveillance (ADS), enhances existing beacon surveillance applications, and also provides new surveillance, data-link, and navigation capabilities.
- The airborne-surveillance, surface-surveillance, and data-link capacity of GPS-Squitter satisfies current and future FAA surveillance requirements.
- GPS-Squitter can provide significant improvements to TCAS operation while maintaining TCAS as an independent safety monitor through active validation of GPS-derived position reports.
- Because Mode S is an internationally accepted operational system on the beacon frequencies and the addition of the long squitters causes a negligible increase in channel occupancy, there should be no spectrum-allocation problems.
- GPS-Squitter builds on the Mode S air and ground equipage now under way and requires only minor modification to existing Mode S transponders.
- A single Mode S transponder provides both ADS and beacon radar capability, thus ensuring both compatibility with existing beacon installations and operation in regions using ADS as the surveillance technique.
- This interoperability permits a smooth transition to ADS and is unique to GPS-Squitter among the techniques that have been proposed to implement ADS.
- Independent range measurements can be made with the Mode S active interrogation protocol to validate the reliability of passively received ADS position reports.

Acknowledgments

The authors wish to acknowledge the valuable contributions made by the FAA sponsors of this program: Ron Jones (ARD-60), Carmine Primeggia and P. Douglas Hodgkins (ASE-300), and John Heurtley (ARD-50). The authors also wish to thank the many members of the Air Traffic Surveillance Group and the Lincoln Laboratory Flight Facility who implemented the experimental equipment and planned and conducted the many successful field experiments.

REFERENCES

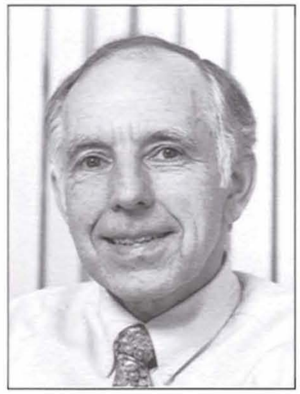
1. V.A. Orlando, "ADS-Mode S: Initial System Description," *Project Report ATC-200,* MIT Lincoln Laboratory (2 Apr. 1993).
2. V.A. Orlando and P.R. Drouilhet, "Mode S Beacon System: Functional Description," *Project Report ATC-42, Rev. D,* MIT Lincoln Laboratory (29 Aug. 1986), DTIC #AD-A005056.
3. International Civil Aviation Organization, International Standards, Recommended Practices and Procedures for Air Navigation Services.
4. P.N. Misra, "Integrated Use of GPS and GLONASS in Civil Aviation," *Linc. Lab. J.* **6,** 231 (1993).
5. Honeywell/Northwest Airlines/ARINC Research Corporation, "Limited Installation Program (LIP) Final Report," Pub. No. 16-3841-14-00 (July 1989).
6. D.W. Burgess, S.I. Altman, and M.L. Wood, "TCAS: Maneuvering Aircraft in the Horizontal Plane," *Linc. Lab. J.,* in this issue.
7. D.W. Burgess and S.I. Altman, "TCAS III Bearing Error Evaluation," Project Report, MIT Lincoln Laboratory (in preparation).
8. RTCA, "Minimum Aviation System Performance Standards, DGNSS Instrument Approach System: Special Category I (SCAT I)," RTCA/DO-217 (27 Aug. 1993).
9. E.T. Bayliss, "Compact Position Report Coding," Project Report, MIT Lincoln Laboratory (in preparation).
10. V.A. Orlando and W.H. Harman, "GPS-Squitter Capacity Analysis," *Project Report ATC-214,* MIT Lincoln Laboratory (20 May 1994), DTIC #AD-A280037.
11. E. Ringel, "Improved Estimate of ADS-Mode S Capacity," *Proc. 39th Ann. Air Traffic Control Assoc. Convention, Washington, 18–22 Sept. 1994,* p. 135.
12. W.H. Harman, "TCAS: A System for Preventing Midair Collisions," *Linc. Lab. J.* **3,** 437 (1989).
13. V.A. Orlando, "The Mode S Beacon Radar System," *Linc. Lab. J.* **3,** 345 (1989).
14. T. Logsdon, *The NAVSTAR Global Positioning System* (Van Nostrand Reinhold, New York, 1992).
15. E.T. Bayliss, R.E. Boisvert, and G.H. Knittel, "Demonstration of GPS Automatic Dependent Surveillance of Aircraft Using Spontaneous Mode S Beacon Reports," *J. Inst. Navigation* **41,** 187 (Summer 1994).
16. R.E. Boisvert, K.W. Saunders, and G.H. Knittel, "Airport Surface Surveillance Using Differential GPS and the Mode S Data Link," *Proc. ION-94 50th Annual Mtg., Colorado Springs, CO, 6–8 June 1994,* p. 335.
17. R.E. Boisvert and V.A. Orlando, "ADS-Mode S System Overview," *IEEE/AIAA 12th Digital Avionics Systems Conf., Ft. Worth, TX, 25–28 Oct. 1993,* p. 104.

VINCENT A. ORLANDO
is a senior staff member in the Air Traffic Surveillance Group. Since joining Lincoln Laboratory in 1973, he has been responsible for the system development of the Mode S beacon system and its data link. He has also contributed to the development of the Traffic Alert and Collision Avoidance System (TCAS) and the Airport Surface Traffic Automation System (ASTA).

Currently, Vince's principal areas of research include the continued development of Mode S and its data link, and extensions to Mode S such as GPS-Squitter and Mode S surface surveillance. He is also active in efforts to achieve international standardization for these systems, serving as a technical advisor to the FAA on the Secondary Surveillance Radar Improvements and Collision Avoidance Systems Panel, and the Aeronautical Telecommunications Network Panel sponsored by the International Civil Aviation Organization.

Before joining MIT, Vince worked on the development of military command and control systems. The majority of his time was spent on field assignments in Europe.

Vince received a B.S. degree in electrical engineering from the University of Cincinnati in 1957, an M.S. degree in statistics from Stanford University in 1970, and a Ph.D. degree in systems and information science from Syracuse University in 1972. He is a member of Tau Beta Pi and Eta Kappa Nu.



GEORGE H. KNITTEL
is a staff member in the Air Traffic Surveillance Group. An instrument-rated pilot, George is currently the program manager for GPS-Squitter. His expertise is in radar systems, antennas, and electromagnetics. In the field of antennas, he has a national reputation and has served as president of the IEEE Antennas and Propagation Society.

George received B.E.E., M.E.E., and Ph.D. degrees from the Polytechnic Institute of Brooklyn (now the Polytechnic University). He served there as an associate professor until 1972, when he joined Lincoln Laboratory. From 1987 to 1991 he was assigned to the Kiernan Reentry Measurements System (KREMS) on Kwajalein Atoll as leader of the large TRADEX radar.

Over the years, George's work has encompassed small lightweight radar antennas/systems for unmanned aerial vehicles, synthetic- and real-aperture radar systems for stationary target imaging, pulse-compression networks, VHF/UHF communications antennas, monopulse radar antennas, radomes, wave and antenna polarization issues, and phased-array antennas of all types. He has authored numerous publications on these topics and has taught graduate-level courses. He has served as consultant to several organizations, including the National Academy of Sciences, and has traveled to Israel to teach at the Technion.

ROBERT E. BOISVERT
is a staff member in the Air Traffic Surveillance Group, where his current focus of research is on the development and testing of GPS-Squitter. He was also assigned to the Kiernan Reentry Measurement System (KREMS) on Kwajalein Atoll both at the KREMS Control Center (KCC) and at the ALCOR/MMW radars. Bob served as Mission Director at KCC and developed target discrimination and tracking algorithms. At ALCOR/MMW, he led an effort to upgrade a near-real-time satellite imaging system. He has also participated in a number of studies on air defense systems.

Before joining Lincoln Laboratory in 1982, Bob taught for the Georgia Institute of Technology and he has also taught for the University of Maryland—Asian Division. He received a B.S. degree in mathematics from Emory University, and M.S. and Ph.D. degrees in applied mathematics from the Georgia Institute of Technology. He is a member of Phi Beta Kappa, was granted a Presidential Fellowship for graduate study, and was the recipient of an award from Sigma Xi for best Ph.D. dissertation.