Airport Surface Surveillance Using Differential GPS and the Mode S Data Link

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BIOGRAPHIES

The authors are staff members in the Air Traffic Surveillance group at MIT Lincoln Laboratory in Lexington, Massachusetts. Bob Boisvert was the lead engineer for the Hanscom Field GPS-Squitter Proof-of-Concept Evaluation and has over 10 years of radar systems experience. Ken Saunders is the lead engineer for the Logan Airport GPS-Squitter Operational Suitability Assessment and has developed and fielded Air Traffic Control ground systems for the past 10 years. George Knittel is the GPS-Squitter program manager at Lincoln Laboratory. He is a private pilot and has expertise in radar systems, antennas, and electromagnetics.

ABSTRACT

A new concept for providing surface surveillance of aircraft and ground vehicles has recently been tested at Hanscom Field in Bedford, Massachusetts. This concept, known as GPS-Squitter, combines the capabilities of differential GPS for navigation with those of the Mode S data link for communications. Together these systems provide accurate surveillance data along with a positive identification of surface traffic, both very important for an effective surface surveillance system.

The GPS-Squitter concept is based on the use of the Mode S squitter. The current squitter is a 56-bit Mode S all-call reply message spontaneously broadcast by all aircraft Mode S transponders at a 1 Hz rate. This message provides the unique Mode S address of an aircraft and is used by TCAS (Traffic Alert and Collision Avoidance System) for acquisition of nearby aircraft. In the Hanscom testing, this squitter was extended to include GPS-based surveillance information.

Two target vehicles participated in the experiments – one aircraft and one ground vehicle. They determined their position, heading, and speed using differential GPS and automatically broadcast that surveillance information to ground transmit/receive stations using the modified squitter. Differential GPS pseudorange and pseudorange rate corrections were formed by a reference station located at Hanscom Field and were transmitted by the ground transmit/receive stations to the target vehicles.

This paper describes the configuration of the target vehicles, the ground transmit/receive stations, and the differential GPS reference station. Results of the surface surveillance testing are provided including: system coverage, surveillance update rate, and differential GPS data quality. Ongoing testing at Logan International Airport is also discussed.

INTRODUCTION

Several surveillance systems are used to help maintain a safe separation of aircraft while in flight. The Federal Aviation Administration's (FAA) Air Traffic Control (ATC) system operates two types of ground based radars: skin track radars referred to as "primary radars" and beacon-interrogator radars which are called Secondary Surveillance Radars or SSRs. Both radars have scanning antennas and provide the range and azimuth of each tracked target. In addition, the SSRs elicit a response from an aircraft's transponder that contains the identity of the aircraft and, in most cases, its altitude. The surveillance information from these radars is provided to air traffic controllers who use it to direct aircraft in a safe and efficient manner.

To augment the surveillance provided by the ground based radar systems, all commercial aircraft with 30 seats or more are equipped with the Traffic Alert and Collision Avoidance System (TCAS). This system operates in a manner analogous to the SSRs, i.e., it interrogates the transponders of nearby aircraft to determine their position and identity. This surveillance information is provided to the pilot in the cockpit and, if a potential collision arises, an audible traffic alert or resolution advisory is issued. Taken together, primary radars, SSRs, and TCAS provide an effective safety shield against the collision of airborne aircraft.

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The surveillance of aircraft operating on the airport surface is not nearly as advanced, however. Presently, this surveillance is performed primarily by direct visual observation. One or more air traffic controllers view aircraft and other surface vehicles from the "tower cab" of an airport's control tower and issue taxi and take-off instructions. At 30 of the busiest U.S. airports, ASDE-3 (Airport Surface Detection Equipment) radars are being deployed to supplement the direct visual observation, especially in low visibility conditions. These skin track radars, however, will not provide aircraft identity, they have difficulty resolving closely spaced aircraft, and radar reflections off of buildings may result in false targets.

Because of the high aircraft density at airports, the potential for a surface collision exists. Since 1990, there have been 3 major collisions in the U.S. involving surface aircraft (Ref. [1]). Moreover, the accident that caused the greatest loss of life in the history of commercial aviation occurred in Tenerife in the Canary Islands when two Boeing 747's collided on a runway in dense fog. Improved surveillance of airport movement areas would help reduce the possibility of future accidents and would also help to enhance airport efficiency.

The GPS-Squitter concept for airport surface surveillance will provide accurate tracks of airport surface traffic as well as a positive identification of each tracked target. It combines the position determination capabilities of differential GPS (Global Position System) with the Mode S data link for communications. The surveillance data provided by GPS-Squitter could be used by surface traffic automation systems to improve airport safety and efficiency.

SYSTEM CONCEPT

The International Civil Aviation Organization (ICAO) has defined a concept for communications, navigation, and surveillance known as the Future Air Navigation System (FANS). One of the recommendations in FANS is for aircraft to determine their position from a global navigation satellite system (GNSS) and automatically transmit that information to ground controllers. This technique is referred to as Automatic Dependent Surveillance (ADS). GPS-Squitter is a form of ADS.

In the GPS-Squitter concept, an aircraft uses a GNSS system, such as GPS, to determine its location, speed, and direction and automatically transmits that information to ATC via the Mode S data link. In particular, the surveillance information is included in a message that is based on the Mode S squitter.

Current Mode S Squitter

The current Mode S squitter is used by TCAS to detect the presence of nearby aircraft equipped with Mode S transponders (Figure 1). The squitter contains the unique Mode S address of the aircraft and is broadcast once per second. The 56-bit message is transmitted at a 1 megabit per second data rate on the 1090 MHz frequency used by all Mode S transponders.

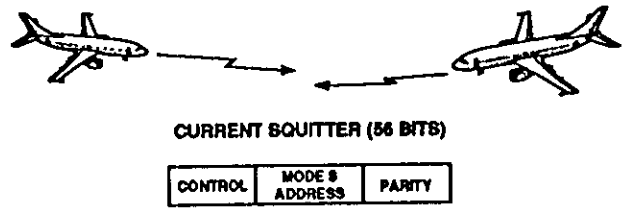

Figure 1. Current Mode S Squitter.

Extended Mode S Squitter

To provide for ADS, an additional 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 message formats, the new squitter would use the longer format allowing 56 bits for the ADS message. For this reason, the terms "extended squitter" and "long squitter" are sometimes used when referring to the GPS-Squitter.

Three types of ADS messages would be used by GPS-Squitter as shown in Figure 2. Two of these provide position information and the third provides the ICAO identification (ID) of the aircraft. One of the position messages would be used when an aircraft is on the surface and the other would be used when the aircraft is in flight. In either case, the position message would be transmitted at an average rate of 2 Hz with some randomization to prevent synchronous garble between two adjacent aircraft. Both types of position messages provide time, latitude, and longitude. The surface position messages also include fields for heading and movement. In the airborne message, these fields are replaced by one for altitude (which would be based on barometric pressure, to maintain compatibility with other aircraft).

The surface position message, shown in detail in Table 1, contains a 4-bit message type field, 7-bit movement and heading fields, a 1-bit time field, 17-bit latitude and longitude fields, and 3 spare bits. To

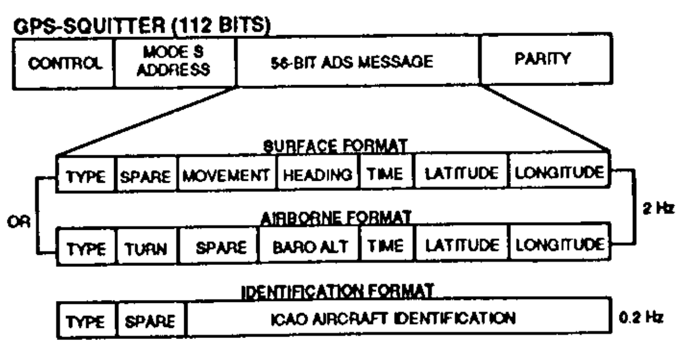

Figure 2. Extended Mode S Squitter Formats.

conserve bits, the GPS receiver would be required to provide a position fix valid on a GPS second mark. When a GPS-Squitter is received by a ground station the only ambiguity on the time of measurement would be whether it was on the current GPS second or the previous one. A bit that indicates even or odd GPS second would be sufficient to resolve this ambiguity. Latitude and longitude would be provided with a least significant bit (LSB) of less than 0.65 meters (the actual LSB is in degrees) with an unambiguous zone 0.75 degrees (45 nmi) wide. A detailed description of both the surface and airborne message encoding may be found in Ref. [2].

Table 1. GPS-Squitter Surface Message Format

FIELD	BITS	LSB	VALUE
TYPE	4	-	8 - dGPS 9 - GPS
SPARE	3	-	-
MOVEMENT	7	-	see Table 2
HEADING	7	2.8°	0 to 360°
TIME	1	1 sec	odd/even
LATITUDE	17	≤0.64 m	0 to 0.75°
LONGITUDE	17	≤0.64 m	0 to ~0.75°
TOTAL	56	-	-

Table 2. Movement Field of Surface Message

LSB/[CODE]	RANGE
≤0.5 kts	Stopped
0.5 kt	0 to 15 kts
1 kt	15 to 80 kts
2 kt	80 to 120 kts
[125]	decelerating
[126]	accelerating
[127]	backing up

On commercial flights, the ICAO ID message would provide the flight number (e.g., AA123) and on other flights it would correspond to the aircraft's tail number. This message would be transmitted once every 5 seconds. Since the unique Mode S address of the aircraft is included in all 3 types of GPS-Squitter messages, the position and ID messages can be correlated by a receive station.

When the standards for the current Mode S squitter were developed, it was envisaged that it may also be used for surface surveillance. Every Mode S transponder has a mode of operation in which it automatically transmits the current 56-bit squitter message at the nominal 1 Hz rate but does not respond to all call interrogations. This mode was intended for use on the airport surface but was never fully developed. The concept called for omnidirectional ground stations to receive the squitter transmissions. Each squitter provides the unique identity of an aircraft, and differential time of arrival (DTOA) techniques would have been used to determine the aircraft position. Unfortunately, DTOA requires that three or more ground stations receive a particular squitter in order to form the position solution. By extending the squitter transmission to include aircraft position, surveillance is possible as long as a squitter is received by a single ground station. A few (1 to 5) stations will be required to guarantee single station coverage of all of an airport's movement areas. The total number of stations required to assure DTOA coverage of the movement areas would be much higher, however.

GPS-Squitter Surface Surveillance

The horizontal position estimates provided by GPS are accurate to within 100 meters 95% of the time even with selective availability (SA) turned on (Ref. [3]). This is sufficient for most airborne surveillance applications of GPS-Squitter, but surface surveillance requires better accuracy. Local Area Differential GPS (LADGPS), however, can be used at airports to provide the necessary accuracy. A differential GPS (dGPS) reference station would be located at or near an airport to form pseudorange and pseudorange-rate corrections for the GPS satellites in view. This correction information could then be transferred to aircraft using a sequence of standard Mode S uplink broadcast messages. These 112-bit messages are transmitted on the 1030 MHz frequency at a 4 megabit per second data rate. Alternately, a Wide Area Augmentation System (WAAS) could be deployed that would use one or more satellites to broadcast dGPS corrections. The FAA is currently investigating the use of satellites in geosynchronous orbit to provide WAAS service for the continental U.S.

The overall concept for GPS-Squitter airport surface surveillance is depicted in Figure 3. At a large airport, a few transmit/receive ground stations would be deployed around the periphery to provide coverage of all of the airport's movement areas. The ground stations would be similar to TCAS units as they also receive at 1090 MHz and transmit at 1030 MHz. Each ground station would use a simple fixed antenna either omnidirectional in azimuth or with some azimuth directivity. A possible ground station configuration is shown in Figure 4.

Each ground station would be able to accommodate approximately 250 aircraft with a 95% probability of obtaining a position update every 1 second (Ref. [4]). At busy terminals, the ground stations would use directive antennas to divide the airport into sectors, thereby increasing the overall capacity to over 500 aircraft.

Other Applications of GPS-Squitter

In addition to surface surveillance, the GPS-Squitter concept will satisfy many other aircraft surveillance applications as well (Refs. [5-7]). Air-to-ground surveillance applications of GPS-Squitter include: en route surveillance, terminal area surveillance, and

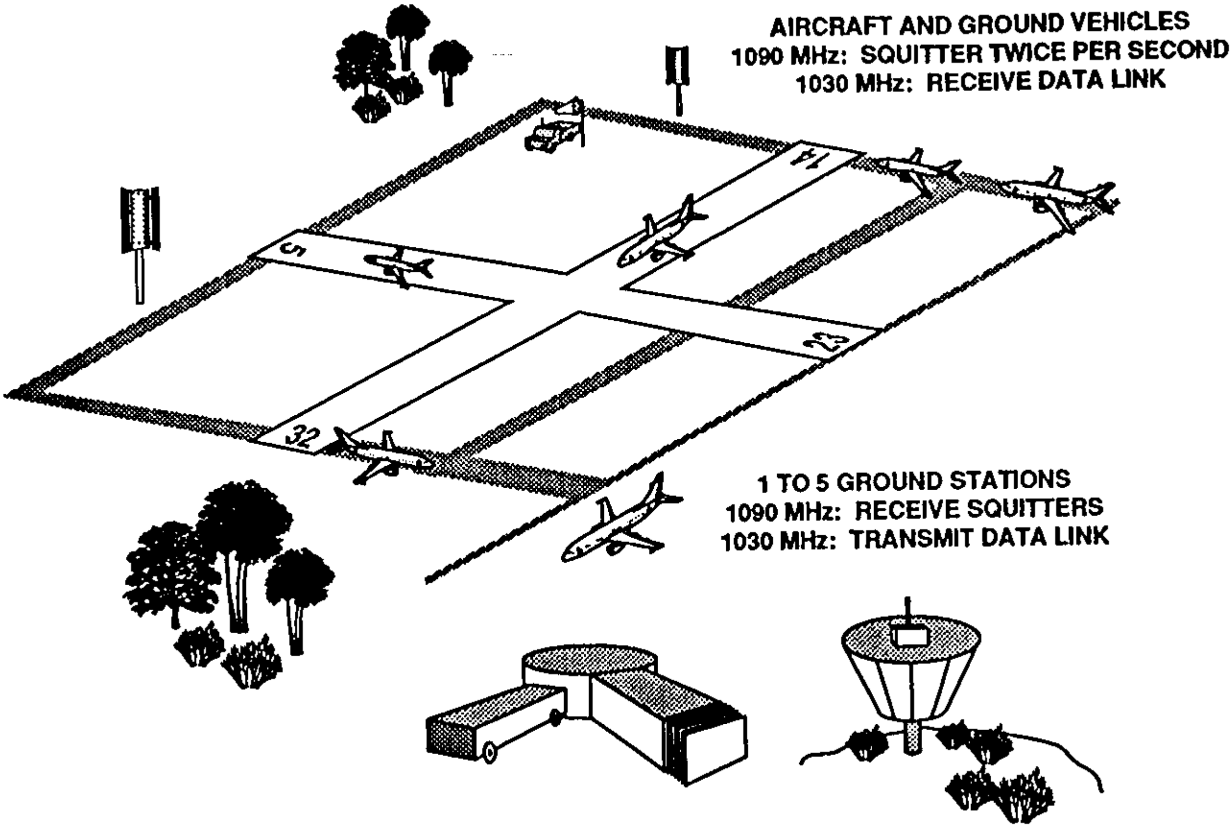

Figure 3. GPS-Squitter Surface Surveillance Concept.

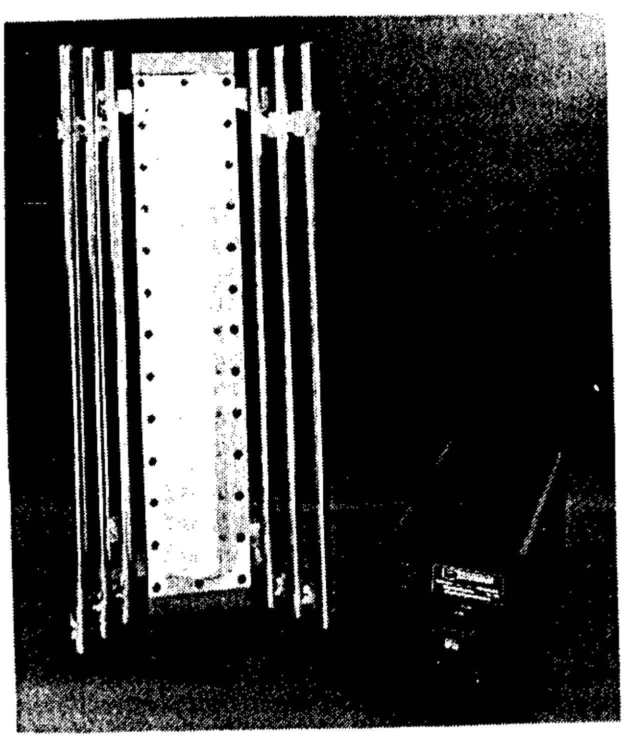

Figure 4. Possible Ground Station Configuration.

precision runway monitoring (PRM). PRM would require the accuracy of dGPS, but unaided GPS, even with SA turned on, would be sufficient for the en route and terminal area applications.

Air-to-air applications of GPS-Squitter include improved TCAS and Cockpit Display of Traffic Information (CDTI). Due to the broadcast nature of GPS-Squitter operation, the position and identification information provided by the extended squitter messages would be available not only to the ground ATC receive stations but also to nearby aircraft. TCAS, which already decodes the short squitters, could easily be modified to decode the extended squitter. This would not only allow TCAS to remain passive most of the time but, due to the improved position accuracy obtained from GPS, it could also allow for horizontal avoidance maneuvers. CDTI is a very simple version of TCAS that provides a display of nearby air traffic but does not issue any conflict or resolution advisories.

In addition to the surface, air-to-ground, and air-to-air surveillance applications described above, the GPS-Squitter ground equipment could perform other applications as well. A dGNSS Instrument Approach System (DIAS) could be based on the dGPS corrections uplinked by the ground stations. The ground stations could also be used for other aviation-related data link applications such as Graphical Weather Service (GWS) and Traffic Information Service (TIS) (Ref. [8]).

HANSCOM PROOF-OF CONCEPT EVALUATION

To demonstrate the feasibility of using the Mode S data link to transmit GNSS derived position information on an airport surface, Lincoln Laboratory conducted a series of experiments at Hanscom Field in Bedford, Massachusetts. These experiments were performed during the Summer and Fall of 1993. The configuration of the equipment used for these experiments is shown in Figure 5. The equipment included: a differential GPS ground reference station; two transmit/receive ground stations; a central control computer; and, two GPS-equipped target vehicles (a Cessna 172 and a surface truck). In addition to a GPS receiver, the target vehicles were also equipped with a Mode S transponder, modified to automatically transmit the GPS-Squitter messages, and a laptop computer for data recording.

dGPS Reference Station

A Trimble 4000RL served as the dGPS reference station. The antenna for this reference station was located on top of a cab on the roof of a hangar building at Hanscom Field. This cab was approximately 80 feet above ground level and will be referred to as the ADS Cab. Pseudorange and pseudorange-rate corrections formed by the reference station were transferred to a Sun Workstation via an RS-232 serial line. The correction data were formatted according to the Radio Technical Commission for Maritime Services Special Committee No. 104 (RTCM SC-104) format (Ref. [9]).

Transmit/Receive Ground Stations

Two transmit/receive ground stations were utilized during the Hanscom Field testing. These ground stations served two basic purposes: (1) they received the GPS-Squitter messages broadcast by the target vehicles; and, (2) they uplinked the dGPS correction information to the target vehicles. Standard Mode S uplink messages known as broadcast Comm A's were used to transmit the correction information.

The two ground stations were developed at Lincoln Laboratory. The first of these was available early in the summer and the second one was assembled towards the end of the experimental period. Each one consisted of an Intel 80286-based single board computer connected to digital and radio frequency hardware. A status monitor connected to each ground station provided information on the messages that were transmitted or received by the sensors. A very simple quarter-wave monopole antenna on a 6-inch ground plane was used by each ground station. The first operational ground station was located in the ADS Cab and the second ground station was located on a building in a different part of the airport (see Figure 5). The height of the antenna for the second ground station was approximately 30 feet above ground level.

Central Control Computer

A Sun Sparc10 workstation served as the central control computer for the experiments. This workstation received the differential correction data from the GPS reference station, reformatted the data into Comm A messages, and passed these messages to one or both of the ground stations. The central control computer also received the GPS-Squitter data from the ground stations, decoded them, and displayed the corresponding target locations in real-time.

Target Vehicle Equipage

The Cessna 172 (C172) aircraft and the surface squitter vehicle were both equipped with the following components: (1) a Collins Mode S transponder modified to automatically transmit GPS-Squitter messages; (2) a Trimble TNL-2100 GPS receiver; (3) an airborne processor; and, (4) a laptop computer. These components are shown in Figure 6.

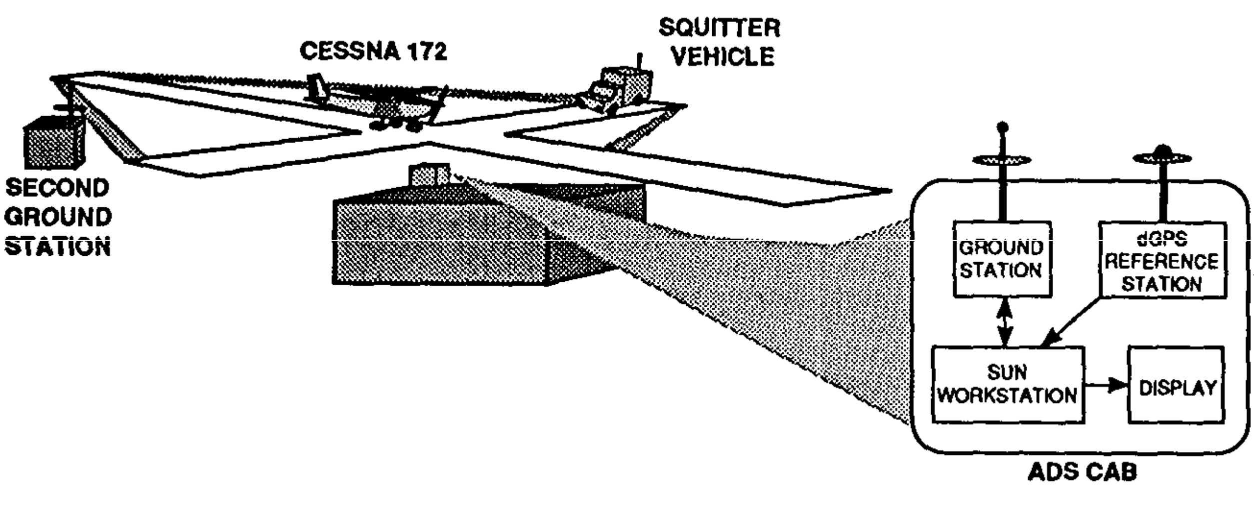

Figure 5. Hanscom Field GPS-Squitter Evaluation.

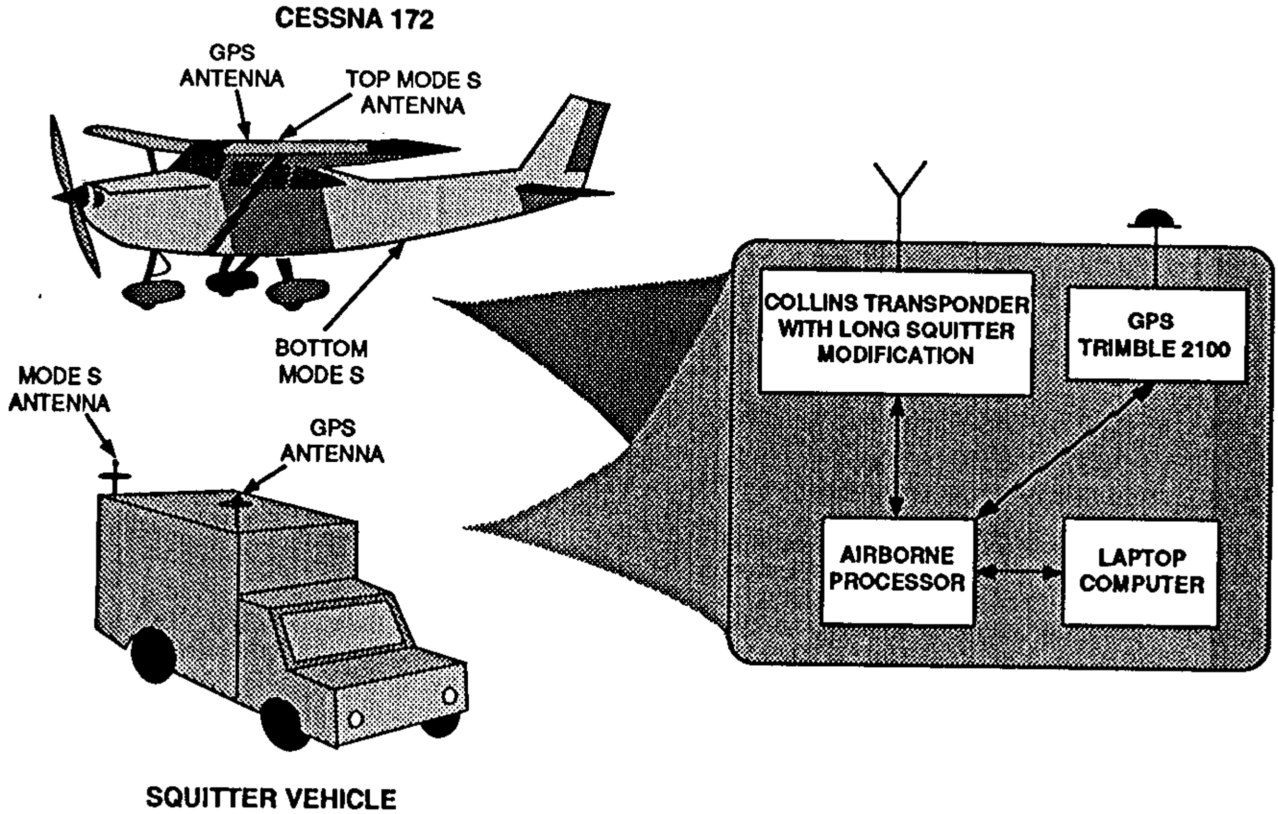

Figure 6. GPS-Squitter Vehicle Equipage.

The transponders were based on Collins TPR-900 Level 3 transponders. Only minor modifications to the TPR-900s were required to add the GPS-Squitter functionality. Within one month of awarding the contract to Collins, the first modified transponder was at Lincoln Laboratory available for testing.

Trimble TNL-2100 GPS units were installed in both of the target vehicles. These are 6-channel receivers capable of processing dGPS corrections. They output navigation information approximately once per second.

A Lincoln-Laboratory-developed airborne processor served as the interface between the GPS receiver and the GPS-Squitter transponder. It consisted of a single-board VME processor and communicated with the transponder over an ARINC-429 interface. The airborne processor created three types of ADS messages (surface, air, and ICAO ID) and sent them to the proper transponder registers. To form the surface position messages, the airborne processor took the 1 Hz Trimble TNL-2100 GPS data and encoded them according to the format shown in Table 1. A similar encoding scheme was used for the airborne position message.

The laptop computer was used primarily to monitor the airborne processor and for data recording. The laptop recorded the GPS and altimeter data used to form the ADS position messages. It also recorded the number of Comm A messages received by the transponder and the number of complete dGPS correction messages received.

HANSCOM FIELD RESULTS

The primary objective of the Hanscom Field experiments was to demonstrate the technical feasibility of the GPS-Squitter concept for airport surface surveillance. This objective was satisfied by setting up the GPS-Squitter system described in the previous section, running real-time demonstrations of the system, and collecting data to assess its surveillance performance.

Real-Time Target Display

A real-time display system was developed for live demonstrations of the GPS-Squitter system and to monitor data collection activities. The display system software resided on the central control computer. An example of the information provided on this display is shown in Figure 7. Arrows, superimposed on a map of Hanscom Field, were used to indicate the location and heading of the surface targets. A data tag was associated with each target. The first line of the tag provided the ICAO ID and the second line indicated target speed in knots. The ICAO ID of the C172 is its tail number (N54715) and for the surface vehicle "MITLLSSV" was used. All of the position and identification information on the target were obtained directly from the GPS-Squitter messages.

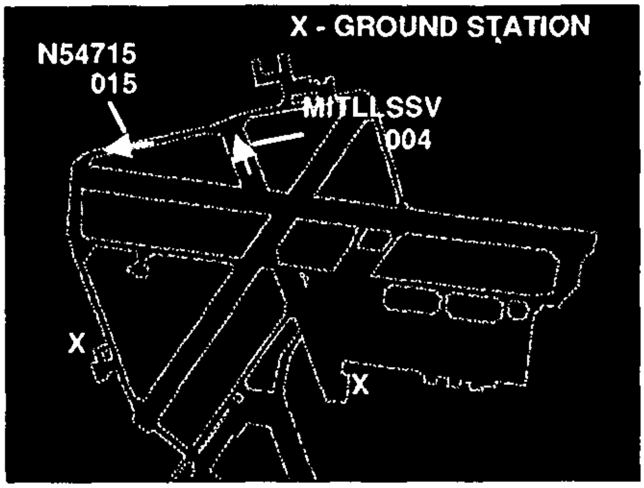

Figure 7. GPS-Squitter Target Display.

Airborne targets were displayed in a slightly different manner. A square symbol was used to indicate position, and altitude was included on the second line of the data tag. Colors were used to distinguish between a target that was reporting a position based on differentially corrected GPS data and one that was reporting unaided GPS information.

The display was extremely easy to read and interpret. Each GPS-Squitter target was clearly identified and there were no false targets. Since the position data is self-contained in the squitter message, a GPS-Squitter transmission that reflects off of a building before reaching a ground station will either be interpreted correctly or discarded as undecodable (each message contains a 24-bit parity field that is used to detect bit errors).

Squitter Reception Reliability

To assess the GPS-Squitter reception reliability, the C172 and the surface vehicle were taxied along the principal taxiways at Hanscom Field. One such track for the surface vehicle is shown in Figure 8. Each dot in the plot represents a one-second position update that was received by at least one of the two ground stations.

For surface surveillance, an update rate of approximately 1 Hz is desired. During the test shown in Figure 8, the ADS Cab ground station received at least one surface position squitter every second 97% of the time and the second ground station provided a one per second update 93% of the time. The combined performance of the two ground stations was 99.8%, indicating that there were very few locations that were not covered by at least one of the two ground stations.

The ADS Cab ground station was used in all of the testing at Hanscom Field. The second ground station was on-line for the last few tests. Figures 9 and 10 summarize the GPS-Squitter coverage from the ADS Cab ground station during the testing. Figure 9 shows the per second GPS-Squitter reception reliability for the C172 averaged over 11 taxi tests. The data are binned into 100-meter overlapping intervals and different symbols are used to indicate the reception reliability within each region. The number that appears in parentheses in the legend indicates the number of occurrences for each reliability level (e.g., there were 112 100-meter intervals that had a per

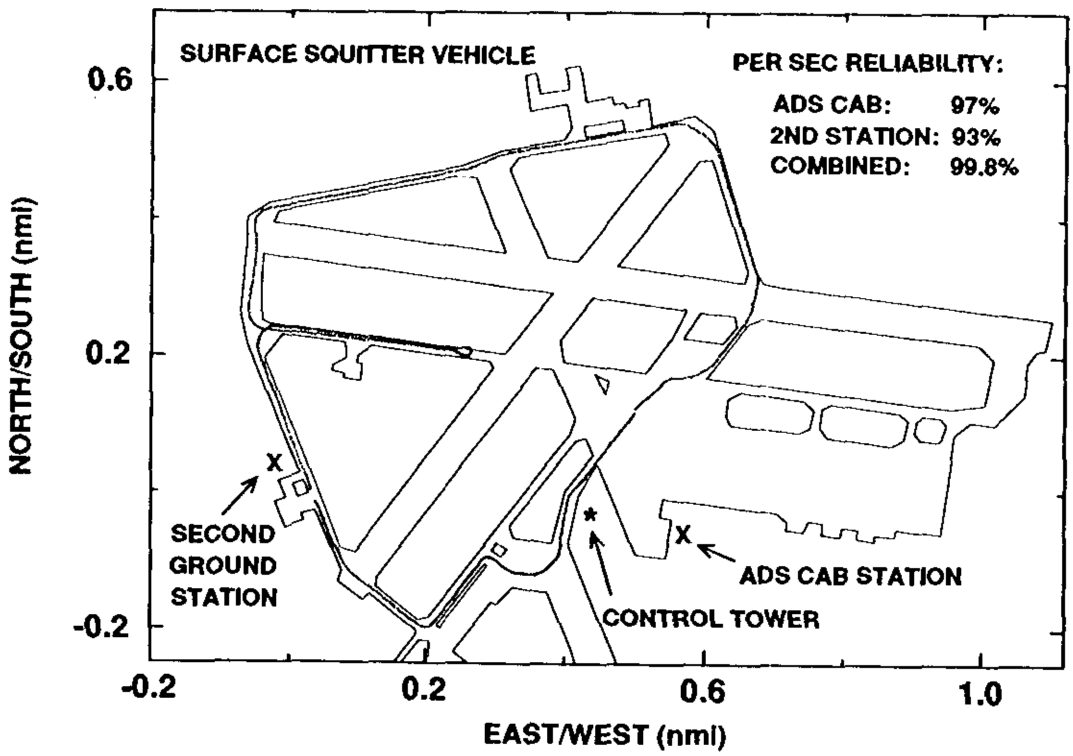

Figure 8. GPS-Squitter Track of Surface Vehicle.

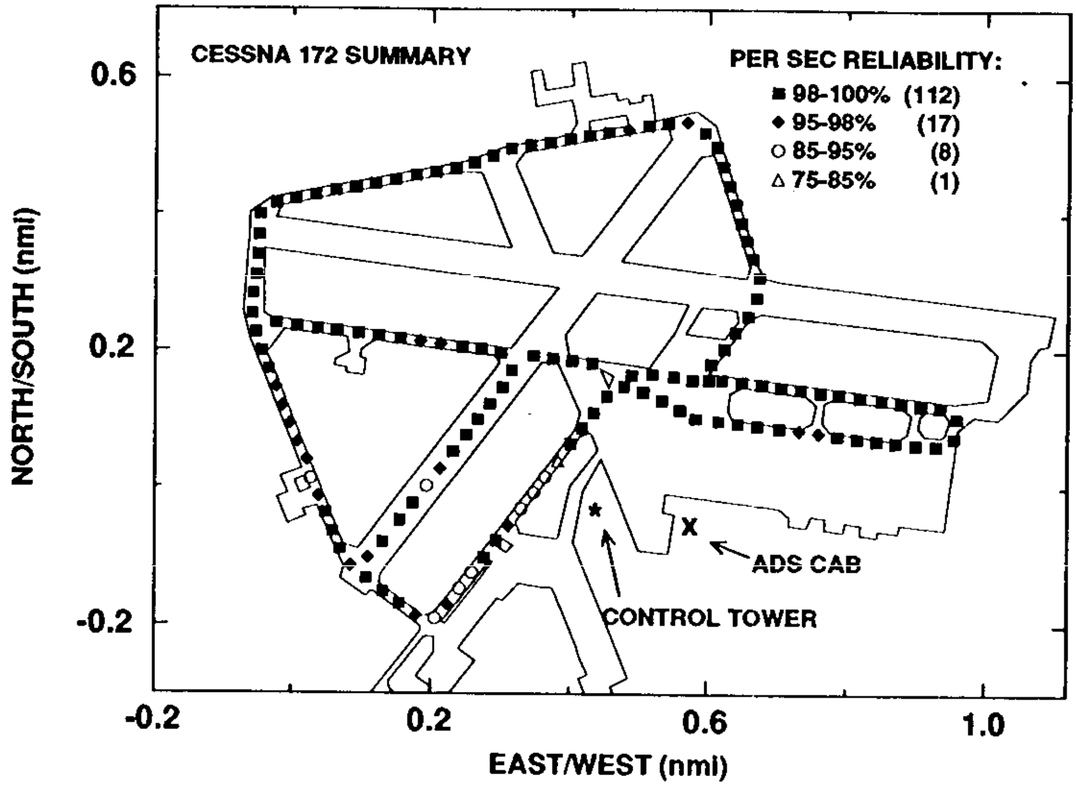

Figure 9. Summary of Cessna 172 Testing With One Ground Station.

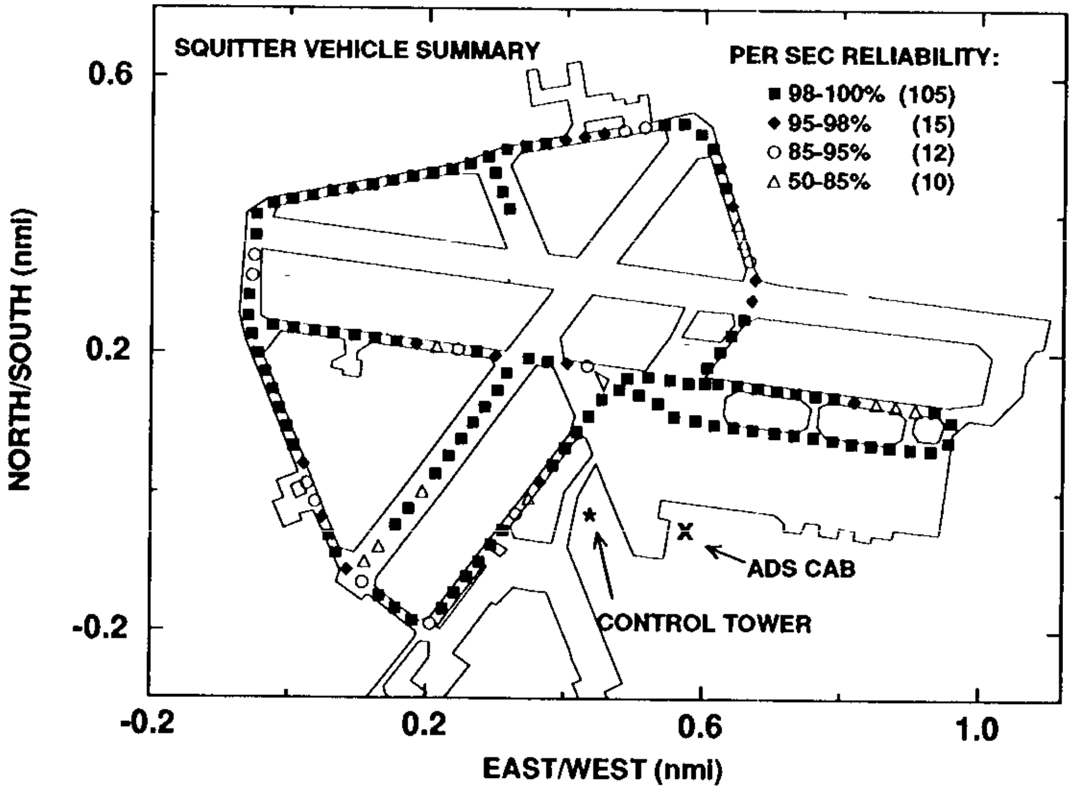

Figure 10. Summary of Surface Vehicle Testing With One Ground Station.

second reliability in the 98-100% range). Figure 10 shows similar data for 18 tests conducted with the surface squitter vehicle.

Four different factors might have prevented the ADS Cab ground station from correctly decoding a squitter message: (1) the squitter could have been blocked by a structure or by another aircraft; (2) a multipath reflection could have produced an interfering signal; (3) an interfering signal could have been produced by a different aircraft; or, (4) the ADS ground station could have been busy uplinking differential corrections when the squitter arrived. The effects of the latter two of these factors were minimal at Hanscom Field. The uplinking of differential correction data occupied the ADS Cab ground station less than 1% of the time and the aircraft density near Hanscom Field is not very high. The effects of blockage and multipath were noticeable in the data, however. The control tower (shown with an asterisk in Figures 9 and 10) did produce a narrow wedge of lower reception reliability, and there are buildings near the taxiways at Hanscom Field that might explain the other regions that did not have perfect coverage. A suitably located second ground station can be used to overcome blockage and multipath problems, as was shown in Figure 8.

The C172 used in the testing at Hanscom has two Mode S antennas – one located on top of the fuselage and the other beneath it. For most of the testing at Hanscom Field, the C172 transmitted the GPS-Squitter messages through the top antenna when it was on the surface, and alternated the transmissions between the top and bottom antennas when it was airborne. This mode of operation is expected to provide the best results for aircraft with top and bottom antennas, as is the case for most commercial aircraft. General aviation aircraft, however, typically have only one transponder antenna mounted beneath the fuselage. For this reason, a taxi test was conducted during which the C172 used its bottom mounted antenna only. Both ground stations were available for this test that had the C172 taxi along the periphery of the airport. The per second squitter reliability obtained by the ADS Cab ground station was similar that obtained in other testing (98%) and the performance from the second ground station was slightly lower (86%). The combined coverage from the two ground station was very good (99.6%).

Uplink Reliability

During the testing at Hanscom Field, differential GPS corrections were provided to the two target vehicles using Mode S Comm A messages transmitted at the 1030 MHz frequency. Although other methods of providing the correction data could be used, the Mode S data link was a convenient one at Hanscom Field and its performance will be briefly reviewed in this section.

The number of Comm A messages that were required to uplink a full set of differential corrections was usually between 8 and 11 (the exact number depended on the number of GPS satellites in view). Data compression could have reduced the required number of Comm A's to approximately 5 but this technique was not used at Hanscom Field. To improve the uplink performance, each set of differential corrections was broadcast more than once from each ground station.

During the test shown in Figure 8, each of the two ground stations repeated a full set of differential corrections 3 times every 4 seconds. After the 4 second period, a new set of differential corrections was sent. The laptop computer on the surface vehicle recorded the time at which each unique set of differential corrections was received. For the most part, a new set of corrections was received every 4 seconds but on one occasion 8 seconds elapsed between the reception of one set of corrections and the next. This reception rate is more than adequate as the Trimble TNL-2100 remains in differential mode for up to 30 seconds after the receipt of a set of corrections and the accuracy of the position fix is good even near the end of the 30 second period. Additional tests conducted with both ground stations exhibited similar uplink performance.

dGPS Data Accuracy

The accuracy of LADGPS position data is reported to be in the 2-5 meter range (Ref. [3]). Although an independent source of truth was not available at Hanscom Field to verify the position accuracy, the data clearly appeared to be accurate enough for surface surveillance. This assessment is based on the following observations: (1) the position of the targets as seen visually closely matched the position shown on the real-time display; (2) when a target followed the centerline of a straight stretch of taxiway, the recorded track exhibited very little variance from a straight line; and, (3) when the target vehicles passed in close proximity to one another, the relative orientation of the vehicles was always clearly indicated on the display screen.

FURTHER GPS-SQUITTER TESTING

An operational suitability assessment of a GPS-Squitter surface surveillance system is presently underway at Logan International Airport in Boston, Massachusetts. The configuration at Logan is shown in Figure 11. For this testing, the Lincoln Laboratory developed ground stations have been replaced by modified TCAS units obtained from AlliedSignal. Four of these have been deployed to provide redundant coverage of all the movement areas at Logan. Early results indicate that the combined performance of the 4 ground stations will provide a one-second position update 99.5% of the time.

The real-time display at Logan shows not only the tracks of the GPS-Squitter targets but also those formed by an experimental primary radar known as ASDE-X. This is a low cost Raytheon maritime radar modified by Lincoln Laboratory for surface surveillance. The ASDE-X and GPS-Squitter tracks have been in very good agreement.

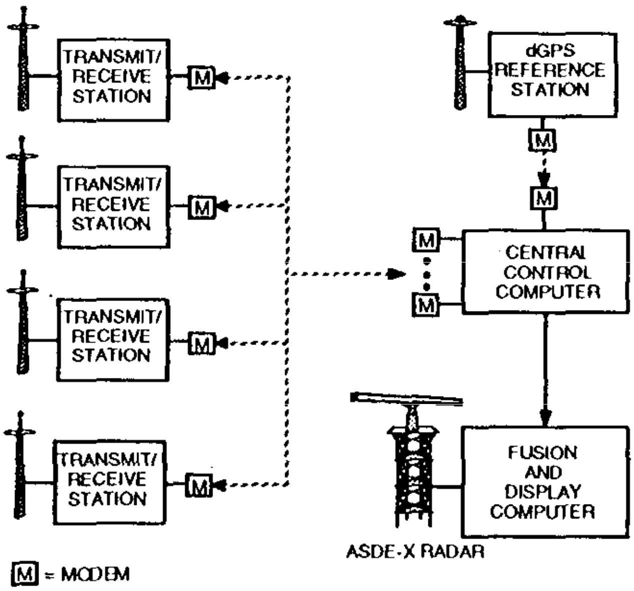

Figure 11. Logan Airport Operational Suitability Assessment.

SUMMARY

There is a pressing need for an airport surface surveillance system that not only supplies accurate track data but that also provides a positive identification of each target. GPS-Squitter will provide such a system by combining the capabilities of a GNSS positioning system with those of the Mode S data link. A minor modification is all that is required to upgrade an existing Mode S data link transponder for GPS-Squitter. Such a transponder will be fully compatible with the existing secondary surveillance system thus allowing for a smooth transition to GPS-Squitter surveillance.

Testing of GPS-Squitter at Hanscom Field has shown that the concept will work well on the airport surface. One ground station provided a one per second surveillance update rate of the primary movements areas' 98% of the time and the combined coverage from two stations provided better than 99.5% reliability. A major airport may require more than two ground stations and the initial testing at Logan International Airport indicates that 4 stations will be sufficient to provide very high reliability. Each station is of low cost, consisting primarily of a modified TCAS unit connected to a simple fixed antenna. The cost of a GPS-Squitter ground station is expected to be less than one-tenth of that of a scanning beacon-interrogator radar.

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