Aircraft Surveillance Based on GPS Position Broadcasts from Mode S Beacon Transponders

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BIOGRAPHIES

The authors, staff members at MIT Lincoln Laboratory, are currently working on the GPS-Squitter program in the Air Traffic Surveillance group.* Edward Bayliss has six years of satellite navigation experience including work on GPS-GLONASS, RAIM, and was lead engineer on the DGPS-Mode S Special Category I precision approach demonstration program. Robert Boisvert was the lead engineer for the GPS-Squitter proof-of-concept demonstration at Hanscom Field and has over 10 years of radar systems experience. Michael Burrows, who recently joined the Air Traffic Surveillance group, has many years experience in antennas and propagation as applied to radar and communications. William Harman has worked on radar surveillance of aircraft since the beginning of the Mode S development in 1971 as well as with air-air surveillance in the TCAS program beginning in 1975.

ABSTRACT

Flight testing of a new air surveillance concept, GPS-Squitter, began during the past year. It integrates GPS receivers with the existing secondary surveillance radar beacon equipment carried by most aircraft. Simple, inexpensive, non-scanning ground stations listen for GPS position reports broadcast by the Mode S beacon transponders on the aircraft and send them on to air traffic control facilities. In addition to its surveillance application, GPS-Squitter presents opportunities for enhancing other important functions such as collision avoidance systems and data link services.

System tradeoff studies are comparing range and altitude coverage with the cost and number of stations needed. Other issues are data link interference, multipath, total aircraft capacity, and unambiguous reporting range. The baseline system uses commercial off-the-shelf components such as TCAS (Traffic Alerting and Collision Avoidance System) avionics units, omni-directional DME (Distance Measuring Equipment) antennas, and computer workstations inorder to ensure low production costs. The cost/performance tradeoff of minimum modifications such as the addition of a 6-sector antenna, multiple receive channels, or higher transmit power, are being evaluated. The omni-directional baseline system is designed for a range of 50 nmi while the 6-sector system is designed for 100 nmi range.

Two aircraft have been equipped with Mode S beacon transponders modified to broadcast (i.e., "squitter") their GPS position twice each second. The numerous test flights have accumulated a significant data base including a demonstration of coverage out to over 100 nmi range. Data have been collected to analyze a number of issues: received power margins, performance of bottom versus top aircraft antenna, ground bounce multipath, propagation over water, and parallel runway approach monitoring. In addition, standard squitter data from commercial aircraft have been recorded and correlated with Mode S tracking to show link margins experienced in practice from aircraft in operational service. More tests are planned, including a demonstration of GPS-Squitter air surveillance in the Gulf of Mexico.

INTRODUCTION

The purpose of the nation's air surveillance systems is to provide the Federal Aviation Administration's Air Traffic Control (ATC) system with the aircraft positions it uses to manage and coordinate aircraft movement. Currently, the main surveillance system is a network of Secondary Surveillance Radars (SSR) which interrogate the beacon transponders carried by most aircraft. This system provides not only the range and azimuth of each aircraft but also its altitude and aircraft ID which are coded on the beacon replies. There are also primary skin tracking radars to provide the range and azimuth of small aircraft not carrying beacon transponders. The ATC system currently relies on voice radio to communicate its control directives to the aircraft.

Beacon systems have evolved as new signaling modes have been adopted over the years. The most recent upgrade, Mode S, reduces link activity by selectively interrogating each aircraft by its unique Mode S address. This mode also makes possible TCAS and the 2-way data link used by TCAS and

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future Air Traffic Management Services. Accuracy and timeliness will be improved once the ATC directives are delivered on this 2-way data link. This upgrade has been implemented by the procurement of 144 Mode S SSRs and the installation of TCAS with Mode S beacon transponders on about 6000 commercial aircraft worldwide.

The International Civil Aviation Organization (ICAO) foresees global navigation satellite systems such as GPS being used for seamless aircraft navigation worldwide. The automatic reporting of GPS aircraft position (called Automatic Dependent Surveillance or ADS) over satellite communication links is envisioned as providing air surveillance over broad ocean and remote regions. Significant economic benefits in these areas accrue from better route management and reduced separation. Over land, however, costly satellite communications are not justified. What is needed here is a more general system that integrates the needs of air surveillance, TCAS, surface surveillance and data link services. Additionally, such a system must transition smoothly from the current SSR system, making maximum use of existing aircraft avionics. These requirements have been synthesized into a new beacon mode called GPS-Squitter. GPS-Squitter offers a natural evolution from the current ground-based beacon system to a GPS-based ADS broadcast system.

The purpose of this paper, a continuation of [1], is to focus on the air surveillance aspect of GPS-Squitter—showing how it works and how it fits into and extends the existing multifaceted air traffic system. In many ways this evolutionary improvement parallels the previous introduction of Mode S into the SSR, TCAS, and data link systems.

GPS-SQUITTER

ADS is implemented with GPS-Squitter by using the aircraft's Mode S transponder to broadcast (i.e., "to squitter") its GPS position twice each second. This broadcast is received by ground-based surveillance stations as well as airborne TCAS units to locate, identify and track aircraft within their region of responsibility. This implementation continues to support SSR beacon interrogations as well as the exchange of data over the 2-way data link (e.g., for TCAS).

GPS-Squitter Message

All aircraft currently carrying Mode S transponders spontaneously broadcast their address once per second in a 64 μs pulse burst (a squitter). TCAS equipped aircraft use this address to keep track of nearby aircraft. The squitter timing is randomized around 1 second to avoid synchronous interference between transponders. The squitter (Fig. 1) contains a control field, the 24-bit Mode S address and a 24-bit parity field to assure high message integrity. The transponders also transmit on request a longer message containing an additional 56-bits of data. At present, these longer messages are sent only in response to interrogations, but for GPS-Squitter, the modified transponder spontaneously broadcasts, as an extended squitter, one of several types of this longer message in which the extra 56 bits contain aircraft position data or the ICAO aircraft identification.

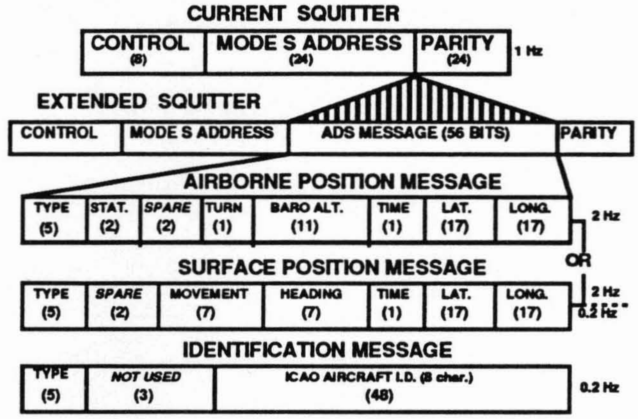

Figure 1. GPS-Squitter extended squitter formats.

Formats of three extended squitter messages are shown in Fig. 1. The transponder squitters the appropriate (airborne or surface) position message every 0.5 seconds (±0.1 second) and the ICAO flight ID message every 5 seconds (±0.2 seconds).

The airborne position formats were carefully designed to use the minimum number of bits needed to give the aircraft's position unambiguously. The type field gives the accuracy of the position report in terms that can be related to Required Navigation Performance (RNP). The turn field and spare bits are reserved to indicate maneuvers or intent information that cannot be deduced from position data alone. The barometric altitude from the standard altimeter is encoded with a resolution of 25 ft. The GPS position is synchronized to the nearest UTC second so that only 1 bit is needed to indicate if the report is for the even or odd second. The latitude and longitude are encoded so the LSB will be about 5 meters worldwide. A seamless encoding algorithm was developed [2] that allows each coordinate to be expressed in 17 bits rather than 23 bits. Details of the surface formats were described in a previous ION paper [3].

Air Surveillance Ground Stations

Air surveillance coverage for SSRs varies from 60 nmi range for a terminal area sensor to 240 nmi for an en route sensor. GPS-Squitter ground stations can be designed for a fraction the cost of these large rotating radars. The basis for the GPS-Squitter ground station is the TCAS unit that has been developed by a number of manufacturers and is currently installed in over 6000 aircraft. These units are designed to receive the short Mode S squitters as well as interrogate nearby aircraft to obtain range, altitude and bearing. Minor hardware and software modifications allow them to receive the Extended Squitter message transmitted by

GPS-Squitter transponders. These changes plus a fixed antenna provide ranges of 50, 100, and 140 nmi as described in the system design section below. Six modified TCAS units have been purchased from one of the US manufacturers. These have been tested with a 50-nmi omni-directional antenna. The fixed directional 100-nmi configuration has been designed and testing will start shortly.

The objective of these GPS-Squitter ground station designs is to make minimal changes to the basic TCAS units to keep their cost low. For the same reason, it is desirable to have a common design for short and long range air surveillance as well as surface surveillance.

GPS-Squitter Applications

The primary applications of GPS-Squitter can be divided into TCAS, surface surveillance, air surveillance, and other areas such as data link applications.

TCAS Enhancements

In dense traffic areas TCAS II must reduce its interrogation range to limit interference to SSRs and other TCAS units. This limits the availability of the traffic advisories in high density areas. With the introduction of GPS-Squitter, TCAS units can operate passively most of the time thus removing this limitation and restoring the traffic surveillance to its full range. With normal GPS accuracy under typical traffic conditions it would only need to use active interrogations once every one or two hours. If both aircraft were using differential corrections to GPS then accuracy would be good enough so active interrogations would be needed only to resolve a potential conflict—something that experience shows only happens once in 45 hours. In addition to reducing interference, the improved accuracy would also permit nuisance alerts to be reduced through miss-distance filtering.

TCAS II cannot make sufficiently accurate bearing measurements to resolve potential conflicts with horizontal maneuvers; it must use "climb" or "descend" advisories. With GPS-Squitter, the more accurate horizontal position would permit the next generation, TCAS IV, to resolve conflicts with horizontal resolution advisories.

These enhancements, primarily in software, could be installed concurrently with the installation of GPS and the GPS-Squitter upgrades to the Mode S transponder. Aircraft thus equipped would start to see benefits from GPS-Squitter immediately. The TCAS units would continue to interrogate non-GPS-Squitter aircraft as before.

Surface Surveillance

Because of the high aircraft density at airports, and the potential for high speed collisions, surface surveillance is one of the FAA's primary concerns. Since 1990, there have been three major collisions of surface aircraft at US airports. At some 35 of the busiest airports, the FAA is installing new ASDE-3 (Airport Surface Detection Equipment) radars which will be a great help in bad weather. They do not, however, provide aircraft/vehicle identification, thus allowing possible confusion of aircraft. This lack of a positive ID, in addition to being a safety concern, also reduces efficiency and presents a barrier to automation.

GPS-Squitter would provide aircraft identification as well as its location. These data can be merged with the ASDE surveillance to identify GPS-Squitter equipped aircraft as well as show the location of non-equipped vehicles. This capability has been demonstrated and is undergoing operational suitability assessment at Logan International Airport in Boston. Results show that four surface surveillance GPS-Squitter ground stations can provide one-second position updates over 99.9% of the movement areas [4].

Air Surveillance

One obvious application for GPS-Squitter is terminal area and en route air surveillance for low to medium density air traffic. For the near future, however, the high density terminal areas will continue to be served by SSRs which have recently been upgraded to Mode S. It is likely that the early applications of GPS-Squitter will be for special situations where air surveillance is needed but installation of fully functional SSRs is impractical. One example of such a situation is the Gulf of Mexico.

Along 800 miles of Gulf coast, oil platforms extend out as far as 120 miles from shore. Personnel transportation to and from these platforms is carried out by some 600 helicopters that can fly up to 9000 flight operations per day with more than 400 in the air at any one time. In bad weather, with no radar surveillance, operations must be curtailed — a very costly situation. GPS-Squitter ground stations installed on a number of oil platforms could provide low altitude surveillance at low cost. A planned demonstration of this application will be discussed later in this paper.

The Gulf also has considerable high altitude commercial air traffic. It, too, has no air surveillance. For safety, therefore, aircraft must be spaced far apart, which lowers air route capacity. Air surveillance provided by GPS-Squitter would allow the capacity to be substantially increased. Consideration is being given to mounting the ground stations on mid-Gulf buoys as well as on oil platforms.

There are many airports in the US that are not busy enough to justify a radar installation. For these airports, in low-visibility conditions, non-radar approach procedures must be followed — resulting in delays as flights are spaced out. A GPS-Squitter ground station at the airport would alleviate this problem.

A number of aging SSRs will have to be replaced fairly soon—before enough GPS-Squitter equipped aircraft would permit a squitter-only air surveillance solution. If they are replaced with simple monopulse

SSRs suitable for low traffic densities but lacking some features of the upgraded Mode S sensors, then it will be possible to augment their coverage with GPS-Squitter ground stations to provide better low altitude coverage as well as data link services.

Other GPS-Squitter Applications

GPS-Squitter is a technology that has the potential for many synergistic system improvements which by themselves may not be justified. Some of these are:

Data Link Functions. Many of the synergistic applications of GPS-Squitter derive from its integral 2-way data link. The FAA's Data Link Operational Requirements Team has identified a hierarchy of services that would be provided to pilots by data link. This includes Air Traffic Management Services (ATMS) which is now exchanged by voice between air traffic controllers and pilots. The high data rate and quick response time of the GPS-Squitter data link make it ideal for such services. While the Mode S signaling standards provide for transfer of messages by using the Aeronautical Telecommunications Network (ATN) protocols, it also provides for a faster, lower-overhead real-time delivery method called Mode S special services. Typical short ATMS messages could be delivered in a fraction of a second by this method.

Traffic Information. The visual display of nearby traffic, such as TCAS provides, has been found helpful to pilots for visually acquiring new aircraft and in maintaining awareness of the aircraft around them. However, TCAS is too expensive for general aviation. Traffic Information Service (TIS) is a less expensive form of air surveillance that can be supplied from the ground-based SSRs over the Mode S data link. An aircraft equipped with a Mode S transponder could request TIS over the data link—the ground sensor then extracts the nearby aircraft (i.e., within 5 nmi in range and ±1200 ft in altitude) from its surveillance file and sends a compressed target list to the aircraft for display on a simple display device. While TIS cannot perform TCAS-type collision avoidance, it can alert the pilot to aircraft that are potential threats. This service is, of course, available only in the SSR coverage area.

Eventually these alerting functions (referred to as Cockpit Display of Traffic Information or CDTI) can be provided onboard each aircraft even outside the SSR coverage area. Once a significant fraction of the aircraft (e.g., >80%) are equipped with GPS-Squitter, direct surveillance of GPS-Squitter reports becomes beneficial. This function would require the addition of a GPS-Squitter receiver to the TIS display equipment. In remote regions, outside SSR coverage area, one can envision the usual visual flight rules of "see and avoid" being extended to the CDTI display—a sort of Electronic Flight Rules.

Weather. Another valuable service available over the 2-way data link is the Graphical Weather Service. This service provides compressed weather maps uplinked on request by the pilot over the Mode S data link. Access to near real-time weather products, en route and terminal, is extremely helpful, especially by GA pilots who do not have weather radars. Text weather reports can also be provided over the link.

TCAS Actions. When a pilot is given a Resolution Advisory (RA) by TCAS in order to resolve a potential conflict, it is important for the air traffic controller to be informed that a maneuver is in progress. When the advisory is issued, TCAS loads a register in the Mode S transponder indicating an RA is underway. A bit is set in a Mode S control field indicating that downlink data are available. The Mode S sensor in terminal areas can read out these data and forward them to the controller. In regions not covered by Mode S sensors these data are available to the GPS-Squitter ground station and would likewise be read out over the data link and forwarded to the controller.

GPS Augmentation. There are air traffic situations in which higher accuracy is needed than GPS alone can provide. Differential GPS corrections are required during surface operations and during precision approach. TCAS surveillance can function passively if GPS-Squitter position data is differentially corrected. The FAA intends to procure a Wide Area Augmentation System (WAAS) which will use geostationary satellites to send additional GPS signals with a) pseudorange corrections, b) GPS satellite integrity data, and c) two additional ranging signals. It is expected that all GPS sets certified for primary navigation will access and use these signals when available.

Augmented GPS can benefit GPS-Squitter by providing integrity and accuracy. Integrity is essential if the GPS-Squitter surveillance system is to rely on the reported GPS position. The GPS solution must be checked for integrity against WAAS integrity data as well as internal consistency checks in the GPS receiver. The differential GPS accuracy provided by WAAS is needed in the terminal area for precision approach and surface operations. GPS-Squitter can also uplink DGPS corrections as a backup to WAAS. This has been demonstrated for both precision approach [5] as well as surface movement operations [3].

Airports with parallel runways with separations between 3400 ft and 4500 ft are allowed to operate the runways independently, thus increasing operational capacity in bad weather. Controllers or automation systems monitoring parallel approaches must have accurate, high rate surveillance of aircraft on final approach. Assuming WAAS is used for improved accuracy, GPS-Squitter reporting at a once per second rate should meet this criteria. GPS-Squitter surveillance for final approaches should be considered as part of siting analysis for the surface surveillance application mentioned above.

The Loran-C area navigation system has been used for navigation in GA aircraft for some time—there are more than 100,000 Loran sets in use. While the decision to retain Loran-C is always subject to review, it may be retained to serve as a backup to GPS. In the event of a GPS failure, the Loran-C position could be used instead in the squitter report.

Complementary Communications. Both the Mode S data link and the VHF Data Link are designed to support the ATN seven layer Open System Interconnection protocol. The physical characteristics of the two links are, however, quite different and inherently complementary. The Mode S data link has a raw uplink rate of 4 MHz with a 34 µs packet size on a single channel while the VHF Data Link uses multiple channels with a 31.5 kHz raw data rate divided among a number of TDMA user slots.

The Mode S data link, owned and operated by the FAA, provides a highly responsive path for real-time ATMS, Flight Information Services (FIS) as well as surveillance and navigation data. It is ideal for short, high priority messages that are typical of ATC communications.

The VHF data link, operated as a private data link with a fee for messages, transports queued, routine point-to-point messages of longer length very efficiently. This is well suited to the longer, routine priority that is typical of Airline Operational Communications.A link loading analysis [6] shows that a single GPS-Squitter ground station can easily handle a 1% data link load (i.e., 294 uplink packets per second) which gives a usable data rate, exclusive of overhead, of 22.5 kbps. The link load imposed by a typical GA aircraft receiving ATMS (i.e., route clearance, routine ATC messages and traffic information) and FIS (i.e., weather text and graphics) will average only 60 bits/sec [7]. Thus a GPS-Squitter ground station could handle routine data link services for an average of 375 aircraft.

AIR SURVEILLANCE SYSTEM DESIGN

Figure 2 illustrates the different elements of GPS-Squitter air surveillance and their location with respect to an airfield. The en route ground stations, with their maximum operating range of 100 nmi or more, and the terminal ground stations, with their maximum operating range of 50 nmi, listen for the extended squitters broadcast by the modified Mode S transponders in the

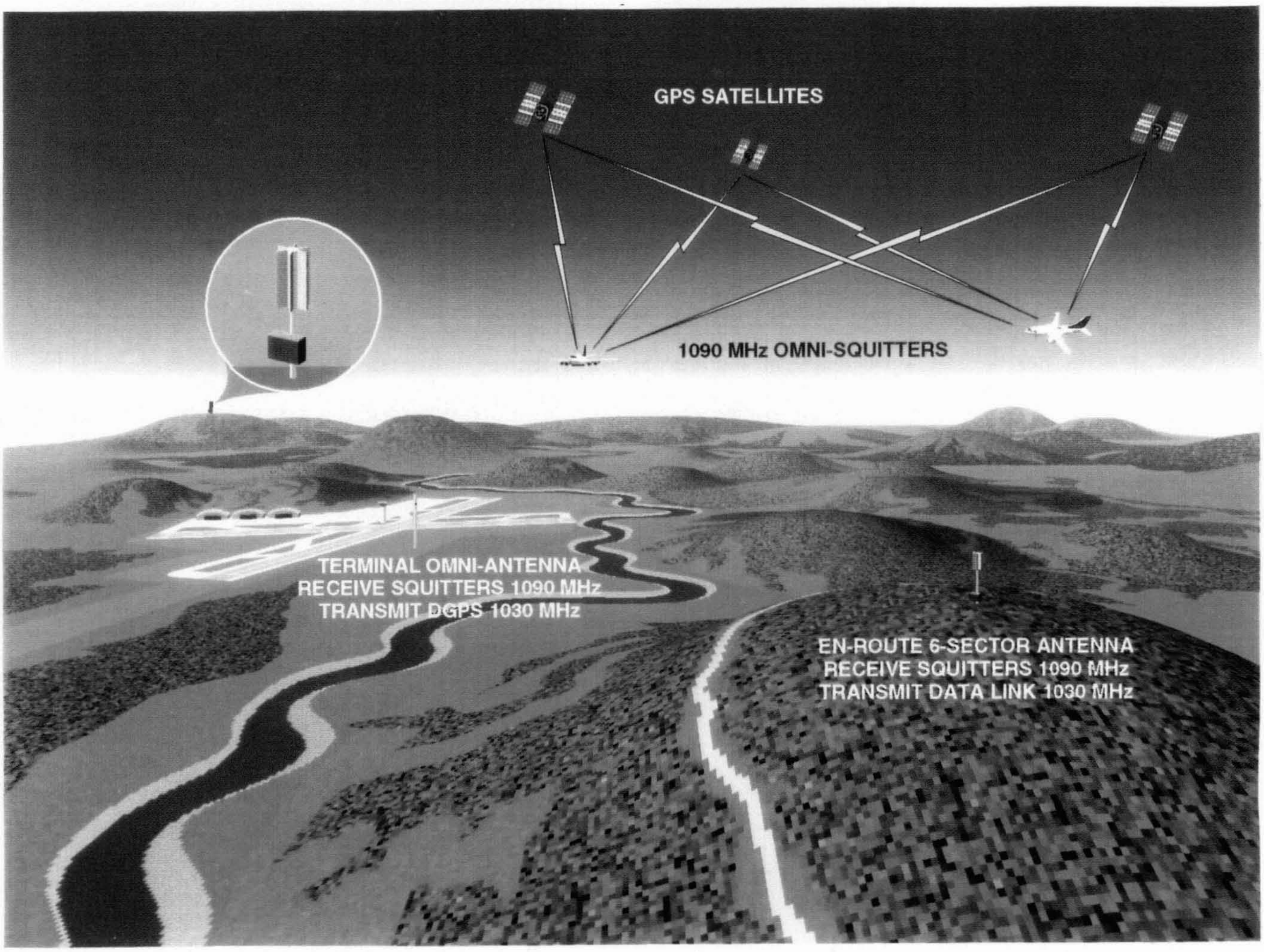

Figure 2. GPS-Squitter air surveillance.

aircraft. The data portion of the extended squitters carries the aircraft's location, derived from the on-board GPS receiver, as well as the barometric altitude of the aircraft and its ID. Interference from other squitters and, especially, replies to SSR interrogations, occasionally blocks the reception of a squitter, but, as analysis described later confirms, the event is sufficiently rare that the system's tracking reliability is not impaired.

GPS-Squitter air surveillance has the significant advantage, indicated in Fig. 2, that its ground stations are, compared with an SSR, small, light and inexpensive. The stations can be wholly pole mounted. Their radiated power is low. These features allow them to be installed in the many smaller airports, where low traffic density doesn't justify the cost of an SSR, and also relax considerably their siting constraints, minimizing blockage by buildings and terrain. They can be spaced more closely than SSRs, which has the double benefit of filling in the holes in the SSR coverage map and providing coverage to lower altitudes. Finally, they can provide data-link services for low aircraft densities.

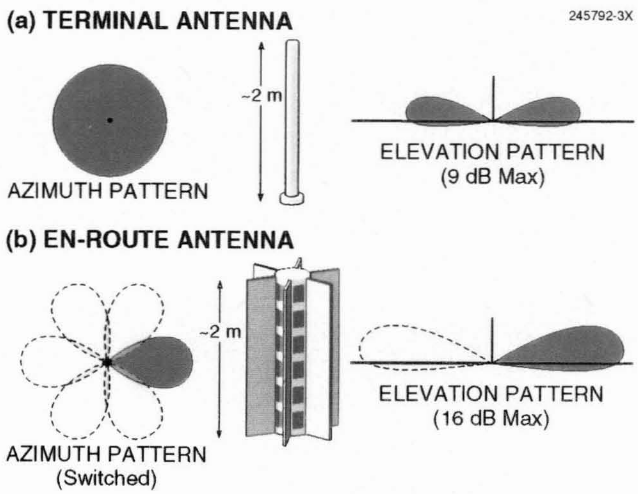

Figure 3. GPS-Squitter air surveillance antennas.

The antennas for the two kinds of ground station are shown in Fig. 3. The terminal ground station uses a commercially available omni-directional DME antenna. It is a vertical linear array fed to produce an elevation pattern with highest gain at low elevation angles, to reach aircraft at long ranges, and low gain at negative elevation angles, to limit signal fading due to ground-bounce multipath. The en route ground station antenna achieves a greater range capability by dividing up the full circle of azimuthal coverage into a number of separate sectors, each with its own receiver. The 6-sector version can be expected to be greater in gain than the omni-directional antenna by some 6 dB, which extends the maximum range from 50 to 100 nmi. The sector design also serves to reduce the incidence of interference (squitters and replies to SSR interrogations) from other aircraft. The antenna trades short range coverage in some directions for longer range coverage in others. Since at long ranges the earth's curvature hides much of the lower altitude traffic, the result is a net reduction in interference.

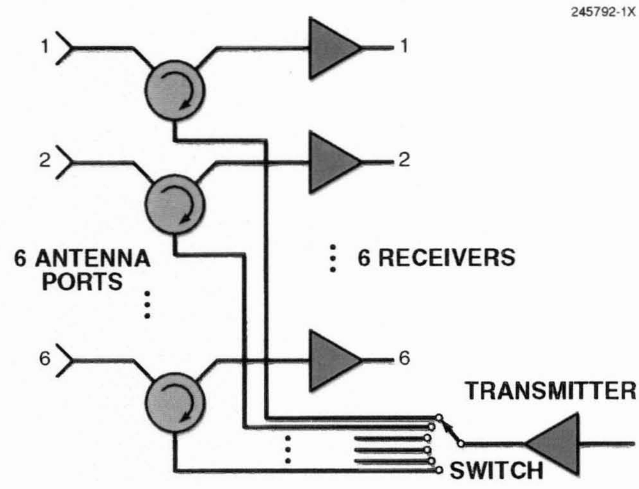

Figure 4. GPS-Squitter ground station.

The ground station, shown in Fig. 4 in its 6-sector en route form, consists of:

- a set of receivers, each one connected to its own separate antenna sector and feeding its own separate decoder
- a single data-link transmitter switchable to any one of the antenna sectors
- a set of circulators to provide isolation between the transmitter and the receivers, and
- a computer processor.

The computer handles decoding, switching the transmitter, and communication via a phone modem link to the ATC center. In the terminal ground station, the number of receivers and antenna ports reduces to just one and the transmitter switch is eliminated.

Link Budget

The downlink power budget for three versions of the ground station is shown in Table 1. The GPS-Squitter air surveillance system relies on receiving squitters broadcast from the aircraft by Mode-S transponders. These transponders are modified for the downlink only to the extent that they can radiate the extended squitters. This implies that to achieve a given maximum range of operation, the only link-budget parameters accessible for shaping the system are the ground station's antenna gain and minimum detectable signal.

For three different versions of the ground station, careful control of the antenna's beam shape can achieve, at the elevation angle of 0.5°, the gains shown in Table 1. When these are coupled with a minimum detectable signal of -82.5 dB, already achieved in a modified TCAS unit, a link margin of 10 dB is attained for all three versions. This margin is required to compensate for signal fading due to ground bounce multipath and to variations of the aircraft antenna gain caused by changes in aspect angle.

Table 1. Down Link Power Budget

System Parameter	Terminal Omni	En route 6-Sector	En route 12-Sector
Transponder			
Power (250 W) (dBm)	54	54	54
Antenna Gain (dBi)	0	0	0
Path Loss (dB) for:	-132.5	-138.5	-141.5
Range, nmi	50	100	140
Receiver			
Antenna	2m Omni	60-deg Sector	30-deg Sector
Gain (0.5 deg) (dBi)	8	14	17
Cable Loss (dB)	-2	-2	-2
Rec. Power (dBm)	-72.5	-72.5	-72.5
Det. Threshold (dBm)	-82.5	-82.5	-82.5
Link Margin (dB)	10	10	10

EXPERIMENTAL VALIDATION

At Lincoln Laboratory, a series of tests of GPS-Squitter air surveillance, leading to a proof of concept demonstration, has already begun. All the necessary equipment is either on hand, or in the acquisition process.

The equipment installed in two light aircraft (a Cessna 172 and a Cessna 421) comprises the following:

- a Mode S transponder (a Collins TPR-900 or a Bendix KT-70) modified to radiate the extended squitters and to receive data link messages
- a GPS receiver (a Trimble 2100, a Litton LTN 1000 or an ARNAV R-5000)
- an airborne computer processor

On the ground, the terminal equipment consists of:

- a Bendix TCAS unit modified to improve its sensitivity, to receive the extended squitters and to transmit data link messages
- a processor and controller resident in a computer workstation
- a dB Systems DME omni-directional antenna

All three components are commercially available.

The en route ground station differs from this in having multiple receivers in the TCAS unit and multiple sectors in its antenna.

The flight tests already carried out are a long-range performance test and flights to measure the interference environment. They are described in the next two sections.

Long Range Performance

The long-range over-land flight test of GPS-Squitter air surveillance was performed on 9 December 1993. During this test, the Cessna 172 aircraft departed from Hanscom Field in Bedford, Massachusetts. Its GPS-Squitter messages were received by a ground station located at the airfield. The purpose of the flight test was to assess the air surveillance capability of a GPS-Squitter ground station equipped with a simple omni-directional antenna.

The ground station was housed in a cab atop a hangar at Hanscom Field and connected to a DME antenna (Fig. 3a) mounted on the roof of the cab. The height of the antenna was approximately 80 ft above ground level. This is the ground station configuration envisioned for the terminal area air surveillance application. As seen earlier (Table 1), a 10 dB link margin is expected out to a range of 50 nmi with this type of system.

The GPS-Squitter track of the Cessna 172 is shown in Fig. 5. On the outbound portion of the flight, the aircraft flew at 10,000 ft altitude and it returned at 9,000 ft altitude. The 4/3 earth radar horizon for these altitudes is indicated in the figure. This horizon estimate assumes a 0.5 degree elevation mask angle for the ground station, which corresponds to the elevation of the tree line as seen from the station. The aircraft flew to a maximum range of 110 nmi, well beyond the nominal radar horizon. The Cessna 172 is equipped with both top-mounted and bottom-mounted transponder antennas and the squitter messages were radiated by alternating between these two antennas.

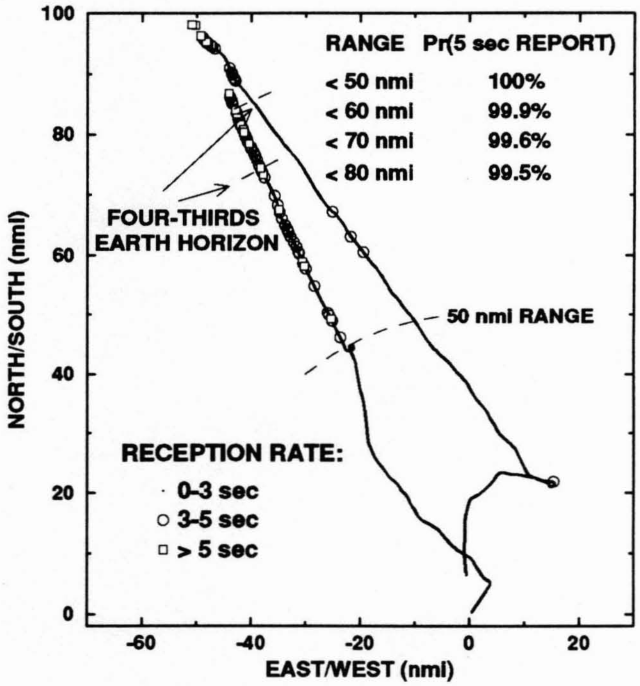

Figure 5. GPS-Squitter long range surveillance.

The GPS-Squitter position messages received by the ground station are plotted in Fig. 5. Three types of symbols are used in the plot: squitters that were received within 3 seconds of the previous squitter are shown as small dots; those that were received within 3 to 5 seconds of the previous squitter are shown as open circles; and, those greater than 5 seconds are shown as squares.

Typical SSR air surveillance update intervals are of 5 seconds for terminal coverage and 12 seconds for en route coverage. During the flight, a 5-second update rate was achieved 100% of the time within 50 nmi of the ground station. In fact, with only one exception, an update rate of 3 seconds or better was achieved out to 50 nmi range. This even included a 360 degree turn executed by the aircraft at the 50 nmi boundary. The excellent performance during the turn indicates that the 10 dB link margin is sufficient to overcome variations in the aircraft antenna pattern as the plane turns. The surveillance beyond 50 nmi range was also very good out to the radar horizon.

The important conclusion to be drawn from this air surveillance test is that there were no unwelcome surprises; the results were consistent with expectations.

1030/1090 MHz Interference Environment

The GPS-Squitter transmissions that report the current locations of aircraft are transmitted at 1090 MHz. The data-link messages and DGPS corrections are transmitted from ground station to aircraft at 1030 MHz. These frequency bands are already being used by the SSR air surveillance system; hence interference effects must be examined.

In the initial assessments of the GPS-Squitter concepts, preliminary analyses were made of a number of possible interference conditions, based on measurements made previously [6,8]. As the system development is now proceeding in more detail, new measurements are being made of the interference environments. Related measurements are also being made to characterize signal strengths and the probability of correct reception as a function of the signal-to-interference ratio.

Many of these measurements are being made with the Airborne Measurements Facility (AMF), developed during the Mode S program in the 1970's [9]. This is a flexible facility for recording 1030 and 1090 MHz receptions, small enough to be flown in an aircraft. In its main mode, it records one word for each received pulse, giving the time of arrival, signal strength, pulse width, and the azimuth angle from which the signal arrived. This can be done for either 1030 MHz or 1090 MHz. The recorded data are processed to identify pulse sequences that are interrogations (in the case of 1030 MHz receptions). It is then possible to determine which interrogations would elicit transponder replies. In the case of 1090 MHz receptions, the post-flight processing identifies pulse sequences that constitute replies, and then counts replies to determine the reply rate.

During this past May, flights were conducted in the Boston area and in a flight from Boston to Philadelphia to remeasure the 1030 MHz interrogation environment. When combined with earlier measurements, the expected pattern of continued reduction in interrogation rate is evident. Following are average rates in the Philadelphia area at altitude of about 6000 ft [10,11]:

Year	Mode A and C Interrogation Rate
1973	300 to 550 per sec.
1978	90 to 120 per sec.
1994	75 to 85 per sec.

In making this comparison, only Mode A and C interrogations from the ground are included. The Mode-C-only interrogations from TCAS aircraft are omitted. Philadelphia was chosen because high rates were measured there before. The reductions are expected because, year by year, the older SSRs are being replaced.

This information is important in the design of the new system because Mode A and C interrogations give rise to Mode A and C replies, which constitute a significant interference environment to GPS-Squitters. The interference environment can also be measured directly, and this is also being done with the AMF. Plans for such measurements include both 1030 and 1090 MHz measurements in a number of major cities. Measurements on the airport surface are also planned. In addition to measuring the rates of interrogations and replies, the AMF is also being used to assess received power levels and the probability of correct reception.

The conclusion is that interference levels continue to decline as old inefficient SSRs are replaced with newer equipment. The results reveal nothing inconsistent with the original positive assessment [6] of the ability of GPS-Squitter to cope with the interference environment.

Future Testing

The next stage in the testing program involves for the first time a multiple sector antenna. The plan is to mount the antenna, together with its ground station equipment, on the hanger-top cab at Hanscom Field in Bedford, MA. Using the Cessna 172 aircraft, tests of reception reliability will be carried out at various ranges and elevation angles, and at the transition between one azimuthal coverage sector and another. The test tracking data will be verified by direct comparison with tracking data taken simultaneously by the Mode S SSR also located at Hanscom field.

The final proof-of-concept test will add two more ground stations, spaced widely from the Hanscom station and from each other. The final ingredient provided by this configuration is the ability to study station to station hand over among netted ground stations. Simultaneous tracking with the Mode S sensor will be carried out here, too. Planned locations for the additional ground stations are Concord, NH, and Barnes, MA. This geometry is shown in Fig. 6.

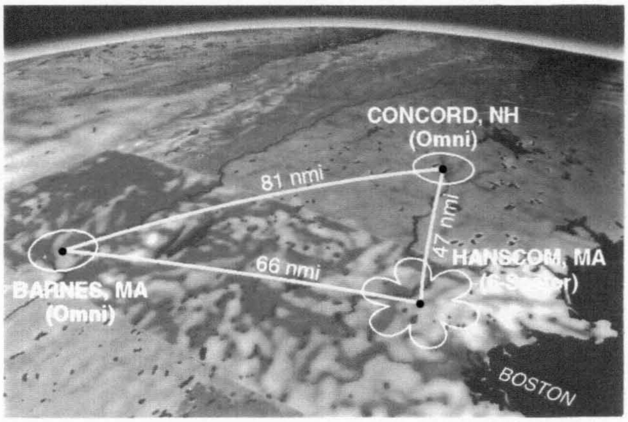

Figure 6. GPS-Squitter netted air surveillance.

In addition to this series of coordinated tests in New England, preparations are being made to carry out a demonstration of GPS-Squitter applied to low altitude air surveillance of oil-rig traffic in the Gulf of Mexico. This is described in the next section.

GULF SURVEILLANCE APPLICATION

GPS-Squitter could provide air surveillance in the Gulf of Mexico, where offshore helicopters are now constrained to follow inefficient non-radar flight procedures. The helicopters, used for moving people and supplies between the mainland bases and the oil platforms, can only fly along radials from the land-based radio navigation stations. The operators need a system giving them the freedom to choose more direct routes between each point of departure and the destination.

This need is expressed as the following set of requirements: The system should provide coverage down to 300 ft for en route traffic and down to 50 ft for approach and departure. The cockpit display must include aircraft ID and position in order to support in-trail flight following. A traffic alert must be presented as a proximity warning not only of nearby aircraft but also of fixed platform locations. An emergency response function is required to identify the closest aircraft or platform. All weather operations must be supported with text or graphic weather displays. Operational communications messages must be relayed (e.g., people on board, fuel on board).

The operational concept is illustrated in Fig. 7. Each aircraft will be equipped with a GPS/Loran

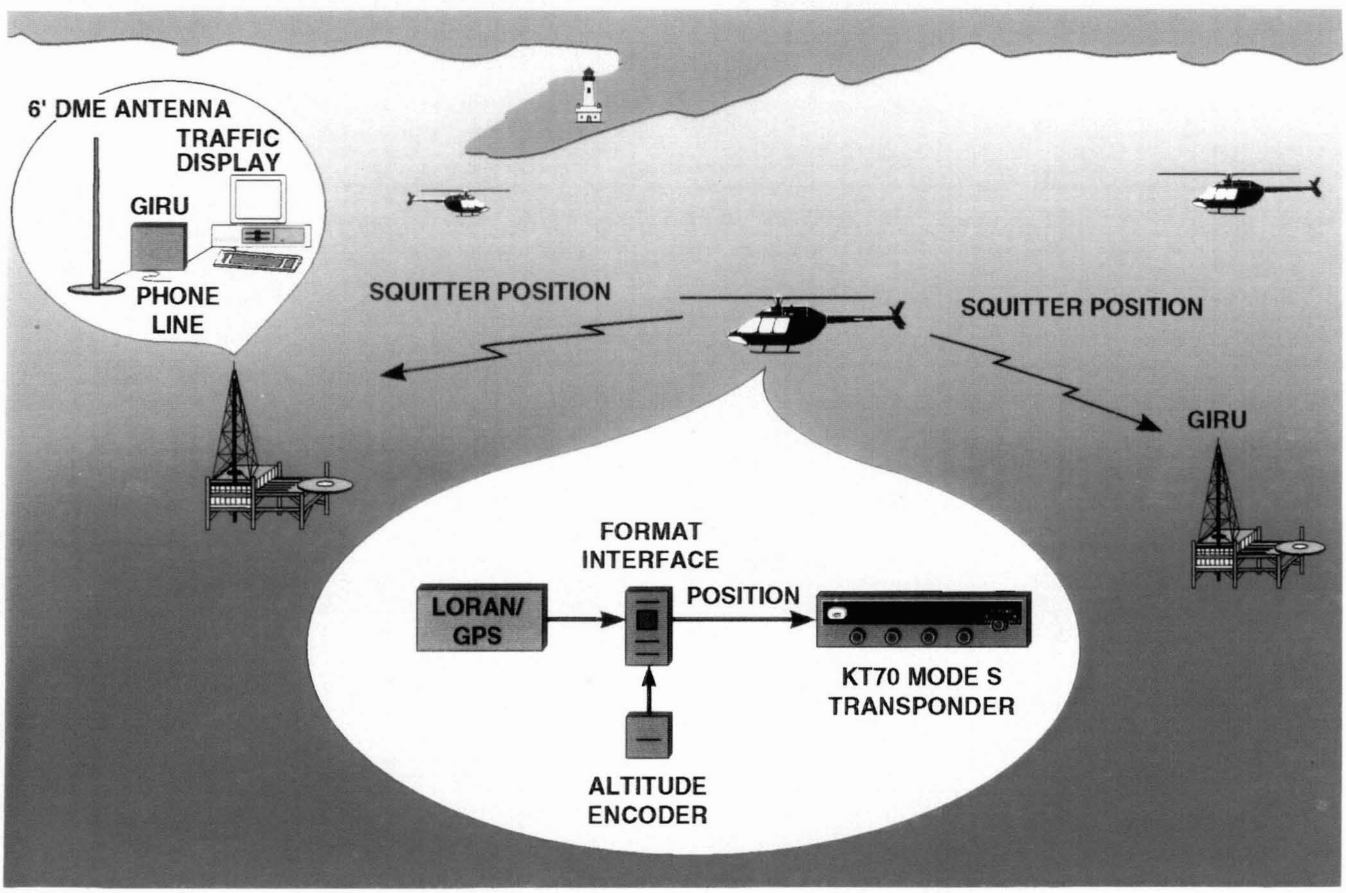

Figure 7. Gulf GPS-Squitter surveillance concept.

receiver interfaced to a Control Display Unit (CDU) which will send position messages to a Mode S transponder modified to transmit GPS-Squitters. A 1090 MHz GPS-Squitter receiver will listen for nearby aircraft and send their position and ID to the CDU for display. The CDU will issue traffic alerts, accept pilot inputs and display outputs from the data link.

The GPS-Squitter ground stations will be mounted on platforms selected to provide the required coverage. Each station includes an omni-directional DME antenna, a ground interrogator receiver unit (GIRU), and a ground station computer. The surveillance data will be sent to the central control computer on the mainland over a standard telephone circuit. For a typical platform installation, a coverage radius of 36 nmi could be expected at 300 ft altitude but only 24 nmi at the 50-ft approach altitude. To cover the platform area, shown in Fig. 8, 14 GPS-Squitter ground stations would be needed on platforms and 7 on the shore.

Initial Demonstration

The special application of Gulf surveillance will be the subject of an operational assessment test starting this fall. One industry supplied GPS-Squitter ground station will be deployed on a platform as shown in Fig. 8 as well as one unit on the shore. Operational range and performance data will be collected under a variety of normal operating conditions. Several aircraft will be equipped in order to test CDTI and flight following operations. The data from the ground stations will be data linked to the Central Control Computers located on the land. Remote displays will be located in Houston and New Orleans.

PERFORMANCE EVALUATION

Efforts are underway in a number of areas to evaluate the performance of the GPS-Squitter system. They address the range of the surveillance coverage from a ground station and system operation in an environment of dense aircraft traffic.

Capacity

The capacity of GPS-Squitter in environments of dense aircraft traffic has been analyzed in a number of respects, and is documented in [6]. A major consideration is the interference from Mode A and C replies to SSR interrogations. This is of concern because of the relatively wide antenna beamwidths of GPS-Squitter ground stations.

The omni-directional GPS-Squitter ground station receives interference from all azimuths, and thus the volume of airspace contributing interference is much larger than that of a conventional radar with a rotating directional antenna. The received interference rate is correspondingly higher. This condition is somewhat offset by the fact that the probability of receiving an individual squitter need not be high. This is true partially because a single squitter is self sufficient for a surveillance update including unambiguous target identification, and partially because the rate of squitter transmission is high relative to the update rate needed for surveillance of airborne aircraft. The squitter transmission rate is 2 per second, which is about 10 times higher than the scan rate of existing radars.

These factors together indicate that the maximum capacity of an omni-directional receiving station is 85 to 280 aircraft within 150 nmi of the station, depending on the interference [6]. The lower number applies to a worst case interrogation environment, a condition that

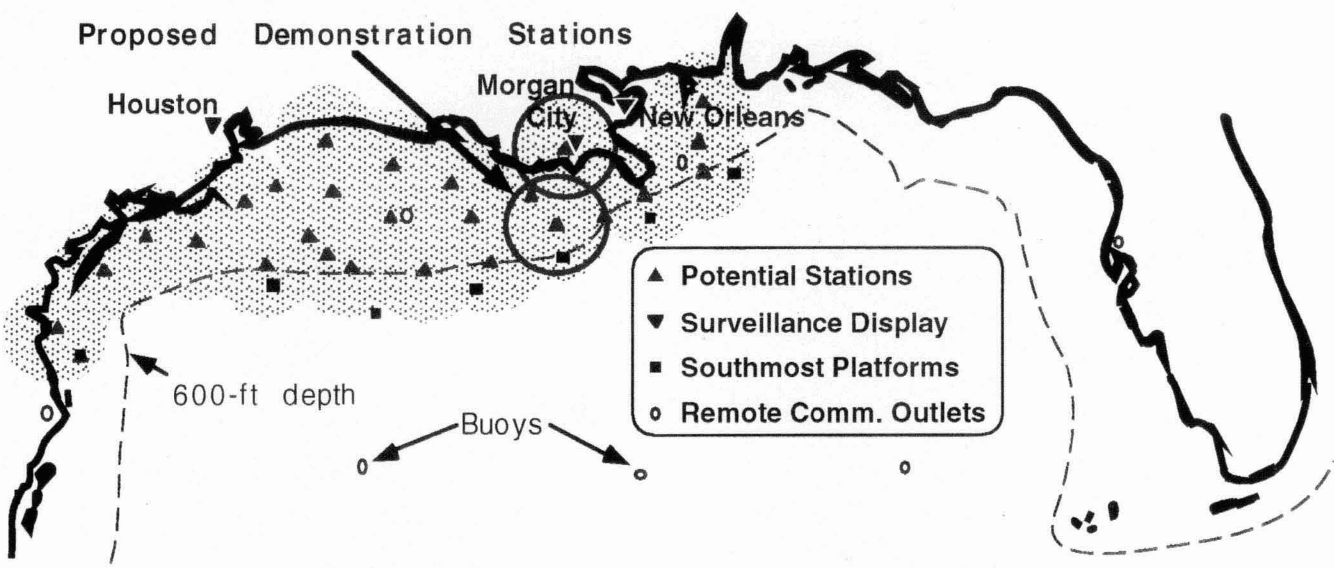

Figure 8. Gulf surveillance coverage.

would improve as GPS-Squitter becomes operational and the older SSRs are replaced. If a 6- or 12-sector antenna is used, reducing the airspace volume from which interference is received, the capacity increases to as much as 700 or 1400 aircraft.

Spectrum Authorization

In the initial concept development of GPS-Squitter, analyses were conducted of interference effects both to and from the system. The results [6,8] were quite positive, and indicated that the functions of the new system could be carried out effectively in practical environments while the signals would not interfere with the performance of existing systems. These results were important in leading to the FAA's decision to undertake a more detailed development of the system.

In transitioning to an operational system, it is necessary to obtain spectrum authorization. The Spectrum Engineering office of the FAA has initiated a process to carry out more detailed analyses of the interference effects to and from GPS-Squitter equipment. Arrangements have been made for an assessment by the Electromagnetic Compatibility Analysis Center, by means of a detailed simulation. The simulation will focus on the Los Angeles basin, and will use the actual locations, power levels, antenna gains, and other characteristics of the radar equipment now in operation in that environment. This work began in the spring of 1994 and is anticipated to yield the major results in one year.

Future Areas of Investigation

Data Link Power Budget. The up and downlink performance of the ground station TCAS units is designed to be balanced. However, efforts have been made to lower the minimum noise threshold level in the ground receiver. It will then be necessary to increase the uplink transmitter power in the ground station to keep the data link balanced. The actual power levels supplied need to be tested and carefully analyzed to verify that adequate margins can be maintained.

Sector Antenna Cross-Over Performance. The 6-sector antenna performance needs to be measured as an aircraft transits from one sector to another. The joint detection probability needs to be evaluated in the overlapped coverage region.

GPS—SSR Reports Integration. A preliminary test of GPS position reports was conducted in Feb. 1993. When GPS positions were correlated with SSR reports a bias in the SSR position reports was discovered. Integration of GPS-Squitter reports with SSR surveillance reports will require more extensive measurements and a thorough analysis of the sources of errors. The planned proof-of-concept demonstration of the sector antenna at Hanscom field will afford an opportunity to correlate concurrent Mode S SSR reports with GPS-Squitter measurements.

Avionics Standards. Standards are essential to the orderly integration of GPS-Squitter functions in airborne equipment. First, minor updates need to be made to the transponder standards (RTCA/DO-181A) to accommodate the extended squitter. Next, TCAS enhancements need to be developed to use GPS-Squitter reports and these must be incorporated into the TCAS standards (RTCA/DO-185). Standards for the GPS receivers under development by RTCA special committee 159 need to include standard outputs to drive the GPS-Squitter avionics. Standards for airborne data link processors (RTCA/DO-219) will also have to handle GPS positions destined for air surveillance. To the extent that inertial navigation and Loran-C are used for a backup to GPS, their interface standards must also be accommodated.

ACKNOWLEDGMENTS

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

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