MULTILATERATION SYSTEM DEVELOPMENT HISTORY AND PERFORMANCE AT DALLAS/FT. WORTH AIRPORT*

M. Loren Wood, MIT Lincoln Laboratory, 244 Wood St., Lexington, Massachusetts 02420

Introduction

Throughout aviation history there has been a small but finite chance of two aircraft colliding in the air or on the airport. Early precautions included flying in daylight and maintaining a "see and avoid" vigil for nearby aircraft. Later, pilots radioed their positions to "controllers" on the ground. The controllers maintained a "situational awareness" and gave instructions when aircraft got too close together. They also ensured coordinated use of the runways and taxiways.

After World War II, because of the growth in air travel, Congress directed the Executive branch to regulate and facilitate aviation. This is now the responsibility of the Federal Aviation Administration (FAA). The FAA formalized the control of aircraft that flew according to a "flight plan", prescribing a departure time, route, and arrival time. One objective of this control was to prevent collisions between controlled aircraft. Two means toward this objective were to provide the controllers with surveillance of the aircraft, and to create a network of three-dimensional highways in the air and rules as to their use.

Two related technologies developed in World War II were applied to provide surveillance. One is primary radar, which provides range by measuring the time between the transmission of a short electromagnetic pulse and the reception of its reflection (echo) off the airplane. The pulse is transmitted over a narrow rotating beam, so the azimuth is taken as the beam's pointing direction when the echo is received.

The other technology is called secondary beacon radar, which evolved out of the WW II Identification Friend or Foe (IFF) system used to prevent shooting down friendly aircraft. It transmits several pulses (called an interrogation) which are received at the aircraft by a "transponder", which in turn transmits several pulses (called the reply). Only friendly aircraft had the transponder, and knowledge of the secret interrogation and reply pulse sequences. The range and azimuth are measured as in primary radar.

The primary and secondary systems are mounted on the same pedestal. Terminal area surveillance is provided by an Airport Surveillance Radar (ASR) having a 60 nmi range and a 4.6 second rotation period. Enroute surveillance is provided by an Air Route Surveillance Radar (ARSR) having a 200 nmi range and a 12 to 15 second rotation period.

The secondary radar is called the Air Traffic Control Radar Beacon System (ATCRBS), having two main interrogations of 2 pulses (P1, P3). The "Mode A" pulse spacing is 8 us, and the "Mode C" spacing is 21 us. All transponders within the azimuthally 4 degree wide beam will reply with a pair of "bracket" pulses (F1, F2) separated by 20.3 us. Between the bracket pulses there is room for 13 equally spaced pulses. In a Mode A reply, the pulses contain an identity code that is dialed in by the pilot at the controller's instruction. In a Mode C reply, the pulses contain the plane's altimeter reading.

To prevent interrogations through the azimuth sidelobes of the main beam, an additional pulse (P2, 2 us after P1) is transmitted by a co-located omnidirectional beam with sufficient power to "cover up" the sidelobes. The transponder only replies if P1 is bigger than P2, which occurs in the main beam. Outside the main beam, the transponder "suppresses". Figure 1 illustrates the operation of the ATCRBS system.

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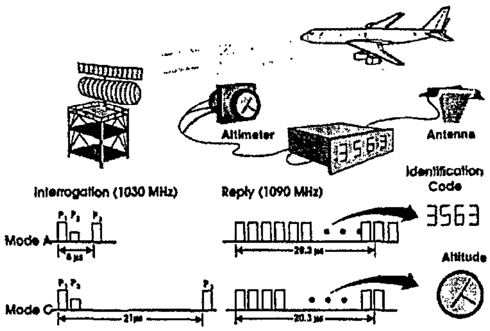

Figure 1. ATCRBS operation

The airspace is partitioned into three-dimensional "sectors", each the responsibility of a controller. He has a Plan Position Indicator (PPI) display which shows the range, azimuth, altitude, Mode A code, and speed for each plane. He communicates with the pilots using a dedicated VHF radio frequency. The sectors are arranged to provide excellent situational awareness.

The ASR does not provide surveillance of the airport surface, so the "ground" controllers maintain situational awareness by looking out the windows of the Air Traffic Control Tower (ATCT), or by observing the PPI of an Airport Surface Detection Equipment (ASDE) primary radar. The ASDE has a 1/4 degree wide beam, a range of about 18,000 feet, and a 1 second rotation period. It is often mounted on top of the ATCT. The ASDE display consists of the radar returns from the aircraft overlaid on a map of the runways and taxiways.

The ASDE detection and accuracy is excellent in favorable conditions. However, the resolution is insufficient to resolve aircraft that are close together, such as when lined up on taxiways or at runway entrances. Also, the performance is degraded in rain, and at some airports parts of the surface are blocked from view by terminal buildings, etc.

False targets caused by reflections sometimes appear. A typical mechanism is when the ASDE pulse bounces off the tail of an aircraft and is reflected toward a terminal building. The pulse reflects off the building and back to the ASDE off the tail, creating a detection at the azimuth of the real aircraft, but at a greater range. When the geometry is just right, the false target appears on a runway, which impairs situational awareness. If the false target appears on a runway when an aircraft is landing or taking off, then the controller must order the pilot to abort the procedure.

There is presently no reliable way to provide the ground controllers with the identity of the aircraft causing a blob on the ASDE display. This impairs situational awareness. If two blobs are heading toward each other, the controller may not always know whom to call on the radio; or, the controller may inadvertently give the wrong aircraft permission to move.

For all of the above reasons, there has been a long search for a technology that would provide aircraft position and identity in all weather over the whole airport. A secondary radar using the transponder would be ideal, but two obstacles would have to be overcome. First, the range has an uncertainty of about 200 feet, due to randomness in the transponder's "turnaround time". The second obstacle is reply garbling when several aircraft reply to the same interrogation.

An early attempt at airport beacon surveillance

In the early 1970's, Bendix Corporation developed a system to overcome the obstacles [1]. The solution to garbling was a technique that interrogated only one aircraft at a time by using two narrow electronically steered beams. The P1, P2, and P3 pulses were allocated between the beams so that an interrogation appeared only at the beam's intersection, as in Figure 2. The beams were then scanned to cover the airport once a second.

To overcome the transponder turnaround time uncertainty, three receivers uniformly spaced around the airport perimeter measured the reply's times of arrival with a quantization of 10 ns (equivalent to 10 feet). The times were differenced (canceling out the unknown reply emission time) and used to form hyperbolas, which intersect at the aircraft's position. This is called multilateration. Within the triangle, and not too close to a vertex, the hyperbolas intersect at reasonable angles so that the positional accuracy is on the order of 20 feet. That is, the "Geometric Dilution Of Precision"

(GDOP) is generally less than 2. The antennas were too expensive to implement the system.

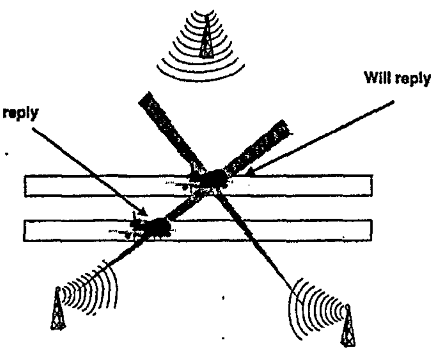

Figure 2. Interrogation by intersecting beams

The Mode S upgrade of ATCRBS

In the 1960's there was tremendous growth in aviation. Rules were made to require transponder equipage in much of the airspace, and many more ATCRBS systems were installed. The beacon frequencies become congested, with predictions for even more congestion. There were more transponders in the beam, leading to more garbling. Since the loading on the reply link is related to the product of the number of transponders times the number of ATCRBS systems, both of which were increasing, ATCRBS was approaching saturation [2].

Therefore, the FAA decided to develop a new system and associated transponder, called the Discrete Address Beacon System (DABS, now called Mode S, for "Selective interrogation"). It was to be backward compatible with the ATCRBS interrogators and transponders. The two main features of Mode S are that each transponder has a unique 24 bit address, and that the antenna can measure the off boresight angle of the received replies [3].

The unique address allows interrogations to be individually scheduled (with knowledge of the range) so that the replies are separated in time, thus eliminating garble as in Figure 3.

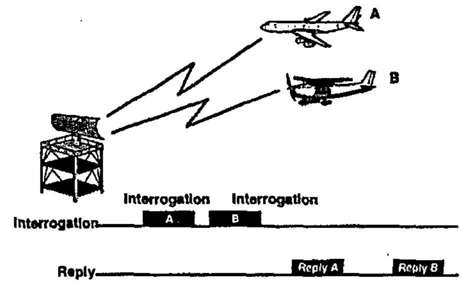

Figure 3. Mode S interrogation scheduling

The off boresight measurement permits accurate azimuth measurements using only a single pulse within a single reply (i.e., monopulse) rather than requiring several replies, and taking the azimuth as the antenna pointing direction when the middle reply is received [4]. Monopulse allows a lowering of the interrogation rate to the older ATCRBS transponders. Mode S standards were adopted by the international aviation community, and the schedule of transponder installation was prodded by the Threat alert and Collision Avoidance System (TCAS).

Collisions between commercial aircraft: TCAS

A principle function of the FAA is the separation of controlled aircraft. Unfortunately, the system is not perfect and collisions have occurred. A famous midair occurred on 25 September 1978, in San Diego, between a Pacific Southwest plane and a Cessna, killing all 135 on the airliner, 2 in the Cessna, and 7 on the ground. A famous runway collision occurred on 27 March 1977, at Santa Cruz de Tenerife Airport, between a KLM Royal Dutch Airlines 747 and a Pan American World Airways 747, killing 582 persons.

The midair collision problem received intense effort in the 1970's, mostly directed toward a system that would use ATCRBS transponders and the new (but not yet implemented) Mode S transponders. The idea was to provide a TCAS aircraft with air-to-air surveillance, and have logic that directs the pilot to ascend or descend to avoid a collision [5]. TCAS surveillance for Mode S and ATCRBS transponders required two developments; a means for TCAS to learn the Mode S address of nearby aircraft, and a way to prevent garbled ATCRBS replies.

The Mode S address problem was solved by adding a spontaneously emitted transponder signal containing the address. TCAS listens for this signal and, when a previously unknown address is heard, makes addressed interrogations to obtain the range and altimeter reading. A small value of the range divided by the tracked range-rate indicates danger. The altitude is used to decide if TCAS should ascend or descend.

The ATCRBS garble problem was potentially worse than for the ATCRBS ground interrogators, because the TCAS antenna is too small to make a narrow beam. The problem was overcome by inventing a sequence of interrogations at gradually increasing power. The lowest power interrogation only elicits a reply from the closest intruder. The higher powered interrogations include a pulse that makes close transponders think they are in the sidelobe of an ATCRBS ground interrogator, so they suppress. The technique is called "whisper shout" and it is effective at eliciting (usually) only one reply per interrogation, even if two aircraft are at the same range. This is because the aircraft tend to have different antenna gains towards the TCAS aircraft. The whisper shout technique is illustrated in Figure 4.

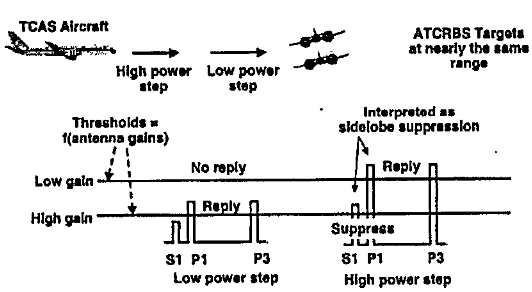

Figure 4. Whisper shout technique

Because the TCAS system was expensive to install on aircraft, it was necessary for Congress to pass a law in the early 1990s requiring installation on commercial airliners. It has prevented several midair collisions, and has vastly increased the pilots' situational awareness.

An attempt at airport beacon surveillance for the military

In the 1980's, the Cardion Corporation developed a military system to provide multilateration surveillance at test ranges [6]. The military used ATCRBS transponders exclusively, and the system proposed to modify them by adding a device ("squitter package") that would make them randomly emit a pair of replies with a precise spacing, as in Figure 5. Three receivers on the ground accept only such pairs, discarding the tens of thousands of replies resulting from hundreds of ATCRBS transponders being interrogated by dozens of ASRs and ARSRs. The system was not implemented.

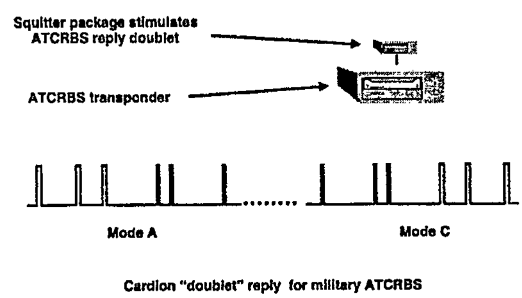

Figure 5. Elicitation of reply pairs

Application of TCAS technology to civilian airport surveillance

Because of the Mode S transponder's squitter, and the whisper shout technique, both of which were developed for TCAS, it was realized that a garble free source of signals for multilateration on the airport was potentially available. There were two uncertainties. First, would the long Mode S squitters successfully propagate in the presence of the buildings on the airport surface. Secondly, would whisper shout work on the airport surface.

The squitter propagation question was favorably resolved by measurements made by Lincoln Laboratory at Boston's Logan airport in 1985 [7].

The question of whisper shout effectiveness was investigated when Cardion built a new system that substituted whisper shout interrogations for the squitter package. It was demonstrated at Atlanta's Hartsfield Airport in 1995.

The effort was funded by an FAA/Lincoln Laboratory contract. To facilitate testing, a practical decision was made to send out the whisper shout interrogations in pairs, using Mode A interrogations (for identity) instead of Mode C (for altitude) as TCAS uses. The technique showed some promise, but it was apparent that requiring two successful interrogations and three receptions of both of the replies was probabilistically demanding [8]. Figure 6 illustrates the multilateration technique tested at Atlanta. The "wing" antennas had gain toward the airport surface.

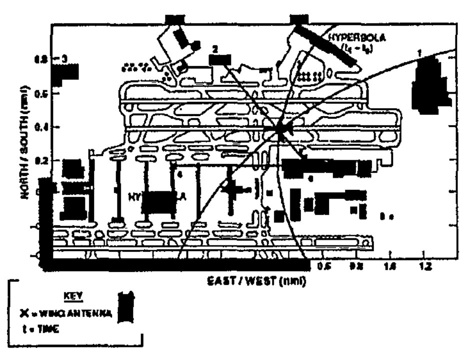

Figure 6. Multilateration at Atlanta

Final system design at Dallas/Ft Worth (DFW) Airport

In 1999, the FAA contracted with the Sensis Corporation to build a new version, using whisper shout with only one Mode A interrogation per power level. Figure 7 shows the signals used for multilateration at DFW. The system was installed on the east side of the DFW airport, and tested extensively under FAA supervision. The remainder of this paper will describe the results.

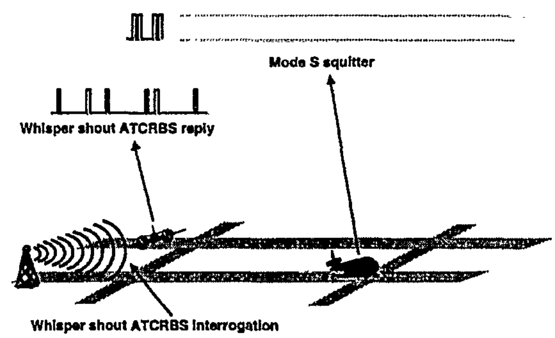

Figure 7. Multilateration signals at DFW

Multilateration Performance at DFW

The tests of the multilateration system at DFW used transponder-equipped test vans, a commercial sized Convair 580 Mode S test aircraft, a small general aviation Saratoga ATCRBS test aircraft, and the operational aircraft of opportunity found on the airport. The coverage, update rate, accuracy, and ability of whisper shout to prevent garbling of ATCRBS replies were all evaluated.

Receiver/transmitter deployment

Figure 8 is an aerial photograph of the DFW airport showing the receiver/transmitter

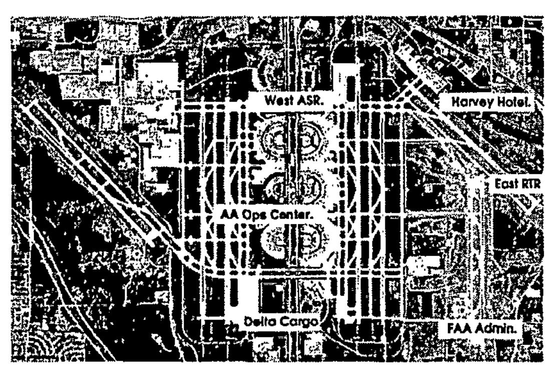

Figure 8. Deployment of receiver/transmitters at DFW

locations, which were selected as the highest available structures uniformly spaced around the perimeter of the east side of the airport.

Coverage

The multilateration coverage was evaluated by taxiing the Convair on the runways, taxiways, and partially into the gate areas. In Figure 9a each dot (overlaid on the aerial photo) is a position where a Mode S squitter was received by 3 or more receiver/transmitters, thus allowing a multilateration position computation. The dots are shown without the photo in Figure 9b. The coverage was 96.8% on the surfaces traveled.

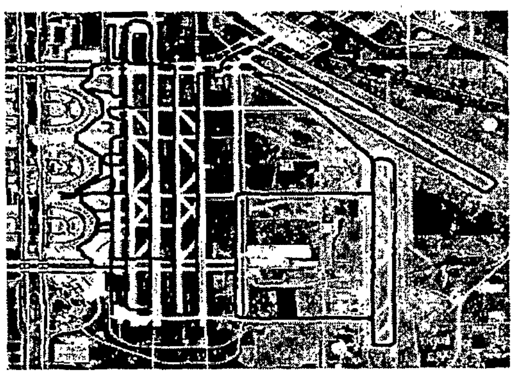

Figure 9a. Multilateration coverage (with photo)

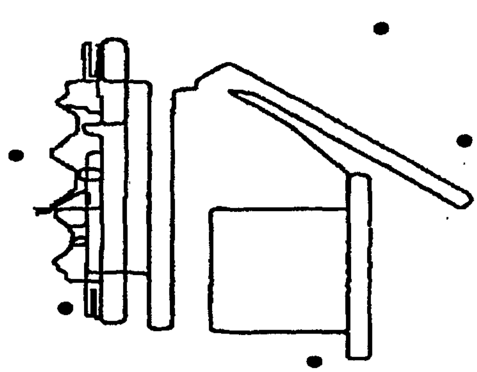

Figure 9b. Multilateration coverage (without photo)

Accuracy

The accuracy was evaluated by driving a van on the runways and taxiways. The van was equipped with a Mode S transponder and with a differentially corrected GPS receiver, which was used to determine the true position of the van. The results for a 3000 by 2300 foot section of the airport are show in Figure 10. The gray dots are the true positions, and the black are the multilateration positions. Each small grid square is 200 by 200 feet. The runways are typically 150 feet wide, so it is clear that the variability of the multilateration positions is a small fraction of the runway width. The sigmas in x and y in the figure are less than 20 feet. The letters identify the runways (35C and 31R) and the taxiways (M, P, Q, and R).

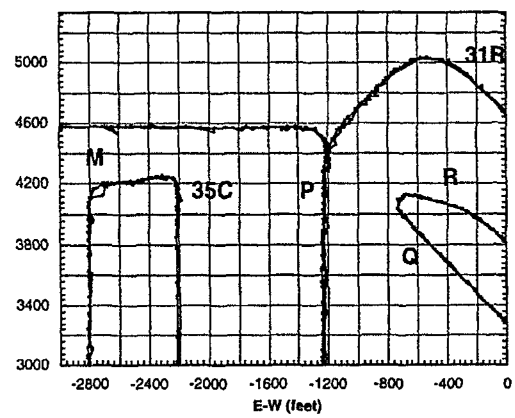

Figure 10. Accuracy

Whisper shout interrogation coverage

The whisper shout interrogation coverage was evaluated by taxiing the Saratoga on the runways and taxiways. The ATCRBS antenna was mounted on the bottom of the fuselage, less than 2 feet off the ground. The results are shown in Figure 11. Each dot is a raw multilateration position of the Saratoga, which indicates that whisper shout successfully interrogated the transponder. (The stray dots are false positions that can be filtered out.) The interrogation coverage is excellent, with only a few gaps near x=5000, y=0. During the test, receiver/transmitter number 1 (RU 1) interrogated intermittently, and RUs 4 and 5 were not interrogating. If they had been interrogating, it is very likely that interrogations would have been successful in the small gaps.

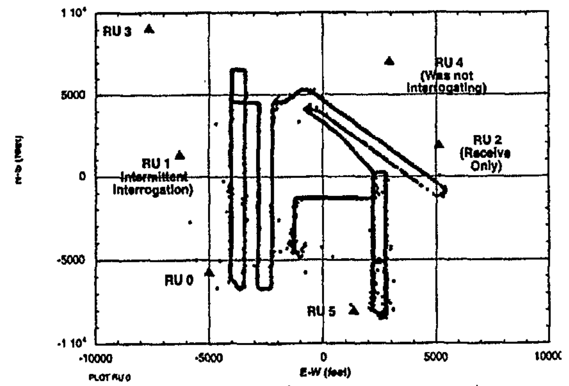

Figure 11. Whisper shout interrogation coverage

Whisper shout degarbling

The ability of whisper shout to interrogate only one transponder per interrogation was evaluated by driving 2 vans equipped with ATCRBS transponders on the runways and taxiways, one behind the other. Figure 12 shows the results. The gray traces show the route of the vans. The black dots are the positions of the vans when they emitted replies to whisper shout interrogations from RU 0, the filled triangle.

The top pair of plots show the replies of the vans to the interrogation that was transmitted with 11 dB of attenuation. Inside the ovals, van #1 replied, but van #2 did not. This means that the receiver/transmitters would receive replies from van #1 that were not garbled by replies from van #2. The bottom pair of plots show that for the interrogation with 19 dB of attenuation, van # 2 replied, but van #1 did not. Thus, in this area, ungarbled replies for multilateration were available for both vans. Examination of similar plots for the other interrogations from RU 0, and from all the interrogations from the other RUs, has shown that ungarbled replies were available at every position on the airport surface that was traversed.

The reason the vans reply to different whisper shout interrogation powers from a given receiver/transmitter is that the antennas have different gains towards the receiver/transmitter, different cable losses, and different transponder receiver characteristics. The gains in various directions are affected by the physical features (tail, wings, etc.) of the aircraft. The tests showed that if the vans did not reply to different levels from a particular receiver/transmitter, then they would do so from some other one. This is because the antenna gains are different toward each receiver/transmitter.

The highest power interrogation has about 50 watts. This power would reach an airborne aircraft about 13 nmi away. On the ground, this power barely reaches across the airport because of a nulling effect caused by partial cancellation of the direct ray by a ray bounced off the pavement.

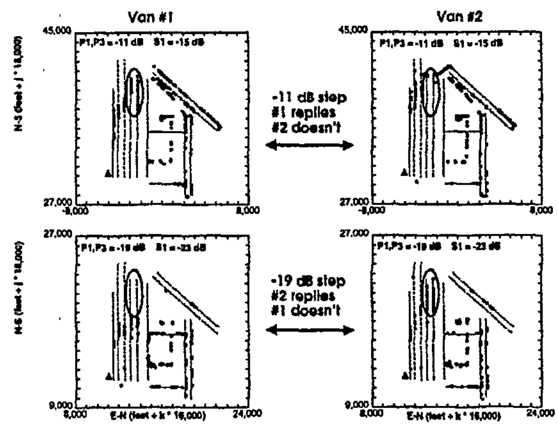

Figure 12. Whisper shout degarbling

Problems encountered

Several problems were encountered at DFW. First, although the intention was that all Mode S positions would be associated with a Mode S ID, and all ATCRBS positions with a Mode A code, other codes were seen. Consequently, dual or triple tracks were formed on the same aircraft. These codes come from Mode C replies (from ATCRBS transponders) elicited by TCAS, and from Mode A and Mode C replies (from both transponder types) elicited by the ASR interrogator at the airport. Techniques are under development to filter out the redundant positions/codes from these replies.

Another problem was incorrect positions caused by replies received via reflections off of buildings. Techniques are under development to recognize and filter out these positions using track history and/or comparisons of arrival times from more than 3 receiver/transmitters.

Compatibility with other systems

The multilteration system shares interrogation and reply frequencies with the ASRs, ARSRs, and TCAS. The multilateration system was designed to minimize its effect on these systems by limiting its rate of whisper shout interrogations. This prevents overloading of the transponders and the other systems' receivers. Tests and analysis have indicated that multilateration will not degrade the surveillance performance of the other systems [9].

Summary and Conclusions

In summary, the long search for a method to provide accurate secondary radar beacon surveillance with aircraft ID over the whole airport surface has succeeded, using the Mode S squitter and whisper shout technologies to provide signal sources on which to make multilateration position measurements. The resulting multilateration system will greatly improve the situational awareness of the ground controllers, and provide inputs to automation functions, providing improvements in airport safety and capacity.

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