Airport Surface Traffic Automation

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Because of a steady increase in air traffic, the Department of Transportation's Federal Aviation Administration (FAA) has instituted a number of programs that are designed to improve safety, reduce delays, and lessen workload intensity for air traffic controllers. The Airport Surface Traffic Automation (ASTA) program, which represents only a small portion of the total FAA effort, uses new technologies and advanced automation techniques to enhance the work of tower controllers, pilots, and vehicle operators. These new techniques are based in part on recent improvements in electronic surveillance, communications, and automation. Surveillance of surface traffic is improved through the use of target data from the new Airport Surface Detection Equipment radar (ASDE-3), or equivalent surface radar, along with the extension of the Mode-S beacon system to the airport surface. Automation processing is improved through new functionality that will be added to the upcoming Tower Control Computer Complex. Finally, tower-to-cockpit communications are augmented by a system of automatically controlled surface lights and a Mode-S two-way digital data link.

According to forecasts by the Federal Aviation Administration (FAA), the number of departure operations at airports in the United States will grow by 30 percent during the 1990s. At a large facility such as O'Hare International Airport in Chicago, which had over 800,000 operations in 1989 and was the nation's busiest airport, this growth translates to an additional 240,000 operations per year by the end of the decade. To meet the challenge posed by this growth, the FAA has initiated a number of major programs to improve airport equipment and traffic control procedures. These efforts range from additional runways (where possible) to the application of new technologies such as advanced surveillance radars, a satellite-based precision navigation system, and automation systems to assist controllers in the management of traffic. Even though new runways, signs, lighting, markings, procedures, and training methods are major items in the overall program, the application of automation techniques offers both the greatest opportunity to improve airport operations and the most demanding developmental challenge.

Air Traffic Control

The tactical control of air traffic in the United States is performed by controllers who are located in three types of air traffic control (ATC) facilities. These facilities, which are operated by the FAA, include 21 en-route control centers, 27 Terminal Radar Approach Control (TRACON) facilities, and approximately 400 individual airport control towers (some of which provide approach-control and departure-control radar services). Figure 1 illustrates these control facilities and how they interact with a typical commercial flight. In addition, approximately 25 non-FAA control towers are operated by private contractors on behalf of state or county governments or large corporations.

The flow of air traffic is primarily determined by the prevailing weather conditions and the location of control zones and other restricted airspace. Weather conditions can be divided into instrumental meteorological conditions (IMC) and visual meteorological conditions (VMC). In general, flight in IMC is conducted under in-

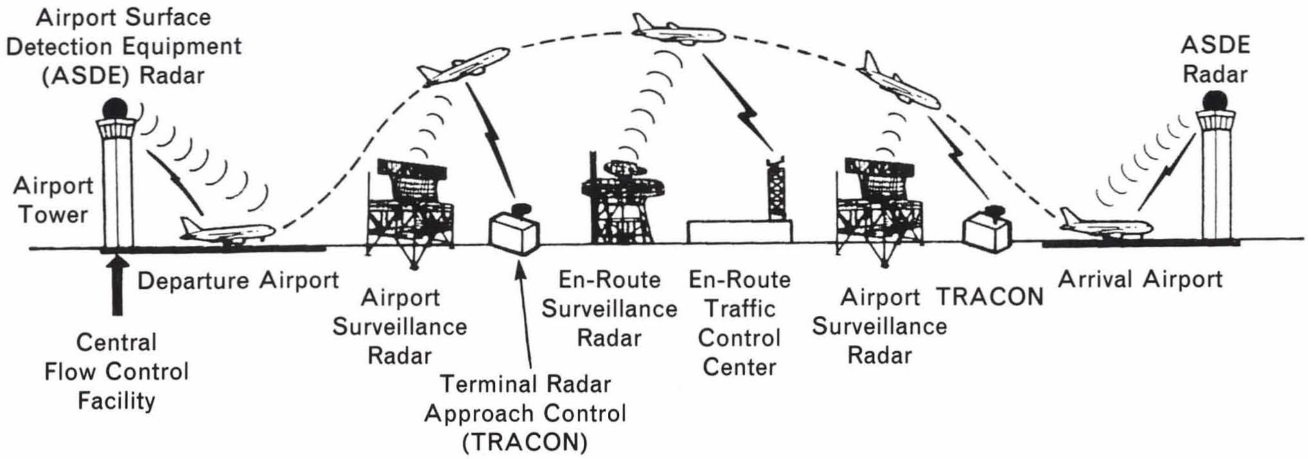


FIGURE 1. The air traffic control system. Tower controllers issue clearances for taxi and takeoff and then turn responsibility for separation from other aircraft over to a departure controller in a Terminal Radar Approach Control (TRACON) facility. Once the aircraft has climbed out of departure control's airspace (typically 10,000 ft), control is passed from TRACON to a sector controller in one of the FAA's 21 en-route traffic control centers. The flight is then handed off from sector to sector until it reaches the vicinity of the destination airport, and a series of approach controllers in another TRACON take over. Because aircraft are arriving from several directions, the controllers must sequence and merge arrivals into orderly streams for the available runways. When the flight is on final approach (approximately five nmi from touchdown), it is passed to a tower controller, who clears the aircraft for landing.

strument flight rules, while flight in VMC is conducted under visual flight rules. Nearly all commercial flights, however, routinely file instrument flight plans and operate under instrument flight rules even when VMC weather prevails. Most of the advanced automation techniques for air traffic control focus on those flights required to operate under positive ATC control, including flights in IMC (based on visibility, ceiling, and clearance from clouds), flights higher than 18,000 ft above mean sea level, flights entering the terminal control areas that surround most major domestic airports, and flights entering control zones around other airports.

The strategic control of U.S. air traffic is exercised by a combination of a Central Flow control function, currently located at FAA headquarters in Washington, and traffic-management units in each en-route control center and TRACON. The role of Central Flow is to prevent traffic overload at key points within the system, such as at major airports, control sectors, and airway intersections. For example, when adverse weather limits the arrival capacity of a major airport, Central Flow implements a ground-delay program that initiates gate holds at other airports for selected flights bound for the critical airport. Weather is the most common cause of ground delays, but the loss of important radar or communications equipment, a temporary shortage of personnel, or temporal variations in traffic are also important factors.

The Role of Automation in Air Traffic Control

Recognizing the need to improve the ATC system, the FAA has initiated a number of new automation-related programs that range from new equipment to new functionality and procedures. The thrust of this effort is defined in a plan to upgrade the National Airspace System (NAS). The centerpiece of the NAS plan is the Advanced Automation System (AAS) program, which is a major long-term effort to replace computers and related hardware within each of the traffic-control en-route centers and the approach/departure TRACON facilities. In addition, as part of the AAS effort, from 150 to 260 of the busiest domestic control towers will receive a new computer system called the Tower Control Computer Complex (TCCC). The TCCC will electronically process flight-progress data, and thus replace the manual effort of passing paper strips in plastic holders from position to position. Other major NAS plan programs include an advanced packet-switched digital communications system known as NADIN II.

The upgraded AAS computer systems are important, but they still focus on moving existing functionalities into newer and more powerful computers rather than adding new capability. The installation of the TCCC at large and midsize airports is an exception because no computer-based traffic-management system is currently located in any domestic control towers.

The Four Major Automation Programs

In addition to the ongoing development of AAS equipment, the FAA is also undertaking four major automation programs to develop new functionality for each of the three control domains. This functionality will first be implemented in a pre-AAS environment and, as AAS equipment becomes available, will later be ported to the appropriate AAS computer system. These programs are as follows:

Automated En-Route Air Traffic Control System (AERA). This system will provide controllers at en-route centers with automation aids that identify potential traffic conflicts and permit controllers to assign direct routes more efficiently. The AERA system, which is being developed by the MITRE Corporation, is expected to reach operational status during the late 1990s.

Terminal ATC Automation/Center TRACON Automation System (TATCA). This system will assist approach and departure controllers at major TRACON facilities

GLOSSARY OF ACRONYMS

AAS—Advanced Automation System

ACARS—Aircraft Communications Addressing and Reporting System

ADS—automatic dependent surveillance

AERA—Automatic En-Route ATC System

AMASS—Airport Movement Area Safety System

ARINC—Aeronautical Radio, Incorporated

ARTS—Automated Radar Terminal System

ASDE—Airport Surface Detection Equipment

ASR—airport surveillance radar

ASTA—Airport Surface Traffic Automation

ATC—air traffic control

ATCRBS—ATC Radio Beacon System

BRITE—Bright Radar Indicator Tower Equipment

ETMS—Enhanced Traffic-Management System

FAA—Federal Aviation Administration

GPS—Global Positioning System

ICAO—International Civil Aviation Organization

IMC—instrument meteorological conditions

NTSB—National Transportation Safety Board

SMGCS—Surface Movement Guidance and Control System

TATCA—Terminal ATC Automation

TCCC—Tower Control Computer Complex

TRACON—Terminal Radar Approach Control

VMC—visual meteorological conditions

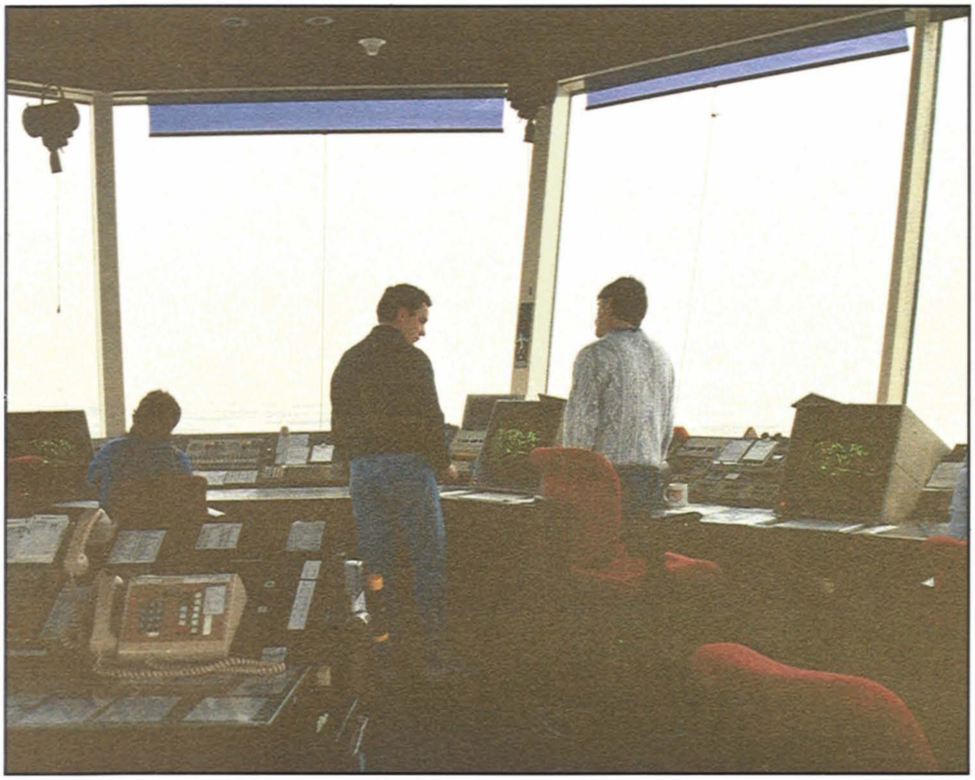


FIGURE 2. The airport control tower is the only location in the ATC system where controllers can actually look out a window to monitor the aircraft. For this reason the tower has been the last ATC domain to be considered for automation. A significant problem in automating the tower is the need to minimize heads-down time, which diverts the controller's attention from viewing the aircraft through the window. Another problem is a lack of physical space to accommodate new equipment. A recent series of surface accidents, however, has resulted in new emphasis on tower modernization with a goal of improved safety.

in the sequencing and spacing of landing and departing aircraft [1–3]. By reducing unnecessary spacing between aircraft during the final phases of flight, TATCA promises to reduce arrival delays significantly at major airports during high-traffic periods. TATCA is being jointly developed by Lincoln Laboratory and NASA Ames Research Center. Initial implementation of TATCA functionality is planned for the mid-1990s.

Airport Surface Traffic Automation (ASTA). This system applies improved techniques of surveillance, communications, and automation to control tower operations to improve surface safety, increase airport capacity, and reduce controller workload intensity. The ASTA program, which is a part of the FAA's Runway Incursion Initiative, initially focuses on control towers at 100 of the most active domestic airports. ASTA is being developed by Lincoln Laboratory and is based in part on concepts originally proposed by W.M. Hollister [4]. The first operational ASTA systems are expected to be commissioned in 1996 or 1997.

Enhanced Traffic-Management System (ETMS). This system will improve the effectiveness of Central Flow and enhance the strategic management of air traffic. The ETMS system is being developed by the Transportation System Center of the Department of Transportation. Initial ETMS systems are now in operation at selected en-route control centers and TRACON facilities.

The Airport Control Tower

The control tower is unique in the air traffic control system because it is the only facility from which the controllers can actually see the airplanes (if visibility permits). Thus the surface-traffic management, including landings and takeoffs, is based almost entirely on human skills (see Figure 2). For this reason, the tower will be the last ATC domain to benefit from advanced automation. Unfortunately, workload intensity, inexperience, and poor surveillance can lead to human error, and thus to a reduction in safety or a loss of capacity.

The most critical tower positions in regard to capacity and safety are those called *local* and *ground*. Controllers in these positions issue clearances to all aircraft that are landing, taking off, and taxiing within that portion of the airport designated as the movement area. This area encompasses all runways and taxiways but excludes ramp and gate areas where aircraft are parked for loading and unloading. The local controller is responsible for aircraft landings, takeoffs, and (at most large airports) all taxiing aircraft and ground vehicles that must either enter or cross an active runway. Although details vary from airport to airport, a local controller's domain generally extends out to five nautical miles from the airport for arrivals and somewhat less for departures. The ground controller issues clearances for all taxiing aircraft and ground vehicles passing between the boundary of the movement area and the point on the airport surface where the local controller takes over. Because of the volume of traffic, most large airports, such as Dallas–Fort Worth, Chicago's O'Hare International, and Atlanta's Hartsfield International, operate what amounts to two airports with separate local and ground controllers for each.

Even though visual surveillance is standard procedure at all airports, local and ground controllers must often rely solely on verbal communications with pilots to obtain surveillance information. This situation is typically caused by weather conditions and the lack of surface radar at all but a few major airports. Inherent limitations in verbal communication, however, frequently result in unsafe conditions and can create a traffic bottleneck. At O'Hare International Airport, for example, the communications capacity of the two ground-control frequencies often limits airport capacity. With peak operations rates exceeding 140 arriving and departing aircraft per hour, the O'Hare controllers are literally talking nonstop, while the pilots desperately attempt to break in to request a taxi clearance or other information.

The Rationale for ASTA

The primary objective of air traffic control is to insure safety. In that regard, controllers have achieved a remarkable record, and the safety of air travel ranks significantly above other means of mechanized travel as indicated by measures such as deaths per passenger mile. A recent transportation safety study compared travel by commercial airline and travel by private automobile, and concluded that any journey of more than 34 miles is safer by air. Even though safety figures for air travel are impressive, however, they still fall short of the ultimate goal of zero accidents and zero injuries or deaths.

Surface Accidents

Most discussions of aviation safety include the surface accident that occurred at the Tenerife Airport in the Canary Islands on 27 March 1977. In conditions of low visibility, the captain of a KLM Boeing 747 mistakenly began a takeoff while a Pan Am 747 was taxiing down the same runway. The resulting accident, which left 583 people dead and ranks as the worst aviation accident ever, was caused by an error in communications.

Because of the unusual geography of Tenerife and advances in technology since the collision, some observers would say that such an accident couldn't happen in the continental U.S. On 31 March 1985, however, at the Minneapolis–St. Paul International Airport, two DC-10 jumbo jets nearly collided when one jet taxied across the active runway while the other jet was taking off. A total of 501 people were on the two planes. A Tenerife-scale accident was narrowly averted when an alert flight crew saw the taxiing DC-10 in their path and forced their jet into the air at below-normal takeoff speed, clearing the intruder by less than 75 ft.

In the history of commercial aviation, surface accidents have been significantly less common than single-aircraft accidents due to weather, mechanical difficulties, and other causes. This situation may change, however, because of growing pressure for increased operational rates to reduce system delays. During a recent 13-month period, three surface accidents occurred at major airports in Atlanta, Detroit, and Los Angeles, with a total loss of 43 lives.

On 18 January 1990 at Atlanta's Hartsfield International Airport, a twin-engine Beechcraft King Air turboprop failed to clear the active runway after landing and was struck by the wing of the Boeing 727 commercial jetliner that followed. The pilot of the turboprop was killed and a passenger was seriously injured. The local controller, who had cleared both aircraft for landing, was distracted by a communications problem with a prior arrival and failed to see the blocked runway.

On 3 December 1990 at Detroit Metropolitan Wayne County Airport, a pilot of a Northwest Airlines DC-9 taxiing from the terminal to the departure runway became lost in dense fog and blundered into the path of a departing Northwest 727 jet. Eight people died and 22 were injured in the accident (see the sidebar entitled "Communications and Tragedy").

On 1 February 1991 at Los Angeles International Airport, a controller became distracted by communications problems with another aircraft and, confused about which plane was which, failed to issue a takeoff clearance to a commuter propjet that had been positioned for an intersection departure. While the commuter jet waited, the controller cleared a Boeing 737-300 jetliner for landing on the same runway. The resulting accident left 34 dead and 26 injured.

Causes of Accidents

These three surface accidents all have human error in common, ranging from a loss of situational awareness to errors in communications and navigation. Better surveillance technology can help to prevent these errors, and an automatic backup safety system can warn controllers and pilots in time to avert an accident. In addition, improved electronic communications such as a two-way tower-to-cockpit digital data link can result in more accurate communications and can reduce loading on voice channels. The objective of these improvements is to help controllers or pilots accomplish their jobs in what is now, and will remain in the foreseeable future, a human-centered system. For this reason, efforts to develop advanced automation techniques must focus on improvements in human performance, which are backed up by automatic safety and traffic-management systems where appropriate. Unfortunately, these specific technological improvements are only now being developed for use in the control tower.

In contrast, large commercial aircraft have used automatic safety systems for many years. For example, the *stick shaker* is an automatic system that vibrates the control stick, or yoke, in the cockpit and alerts a pilot that the air speed has dropped perilously close to stall speed. This type of automatic system acts to prevent a stall by alerting the pilot before the untoward event actually occurs. Other automatic safety systems in the cockpit include ground-proximity warning systems (which are based on radar altimetry) and various configuration warning systems for problems such as flaps not deployed for takeoff or landing gear not down for landing.

Runway Incursions

Preventing accidents is best achieved by preventing the original errors that are usually cited as causal factors in accident reports. With this objective in mind, we focus first on those surface incidents classified as *runway incursions.* The present FAA definition (in simplified paraphrase) of a runway incursion is

> . . . any occurrence at an airport involving an aircraft, vehicle, person, or object on the ground that creates a collision hazard or results in loss of separation with an aircraft taking off, intending to take off, landing, or intending to land.

In other words, a runway incursion is an incident in which the possibility of a high-speed collision exists. Figure 3 shows the numbers of runway incursions officially recorded in the U.S. in the past four years.

The principle causes of runway incursions are classified by the FAA's Office of Safety Analysis as (1) operational errors (controller errors), (2) pilot deviations (pilot errors), and (3) vehicle/pedestrian deviations (errors by vehicle operators or pedestrians). Figure 3 shows an apparent large drop in the number of runway incursions from 1987 to 1988, which is followed by a steady rise during the two following years. The drop from 1987 to 1988 is explained by a tightened formal definition of runway incursions rather than any actual improvement in safety.

FAA Priorities for the Airport Surface

Recognizing the need for improvements in both safety and capacity, the FAA's Air Traffic Requirements service has defined four major priorities for the airport surface. These priorities are (1) a system to prevent runway incursions, (2) data tags on the new ASDE-3 surface radar display, (3) delivery of surface-traffic information to the cockpit, and (4) a method for sequencing departures. The first three priorities relate to improved safety, while

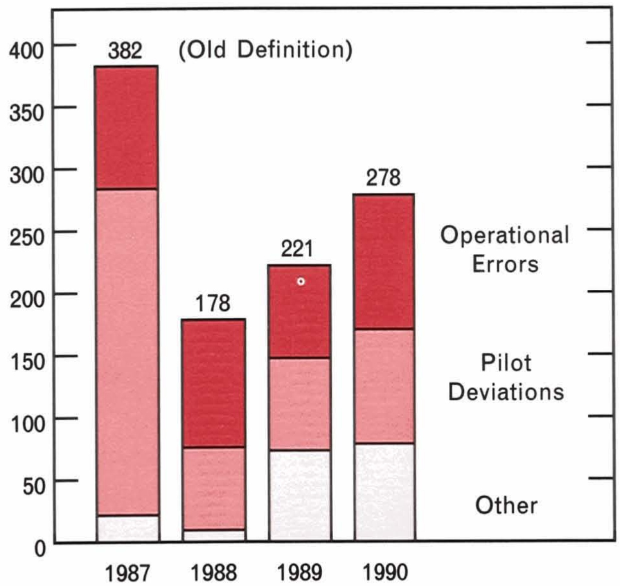


FIGURE 3. Incidence of runway incursions. A runway incursion is an incident in which the potential exists for a high-speed collision. Runway incursions are categorized as operational errors (controller errors), pilot deviations (pilot errors), and vehicle/pedestrian deviations (vehicle operator or pedestrian errors). The FAA's Office of Safety Analysis has reported a steady rise in the number of runway incursions over the past three years. The significant drop in the official count of runway incursions between 1987 and 1988 is attributed to a change in the method of counting incursions.

the fourth priority addresses airport capacity. Priorities 2 and 3 are intended to improve the situational awareness of controllers and pilots, and priority 3 recognizes the need to assign the pilot a greater share of responsibility in preventing runway incursions. Priority 2 depends on the availability of the new ASDE-3 high-performance surface radar. This unit is currently in early production and is scheduled to be installed at 29 of the largest domestic airports within the next two years.

The Three Phases of the ASTA Program

The ASTA program currently being developed by the FAA has three overlapping phases: ASTA-1, ASTA-2, and ASTA-3. ASTA-1 is a radar-based safety system that includes the automatic detection of runway incursions and other movement errors, audible and visual alerts for controllers, and a system of automatic runway-status lights intended to improve the situational awareness of pilots and vehicle operators. In addition, the FAA is undertaking an early implementation of another automatic alerting system known as the Airport Movement-Area Safety System (AMASS). AMASS will provide the foundation for the implementation of ASTA-1 capabilities. ASTA-2 adds a surface beacon surveillance system for positive identification of all Mode-S and other transponder-equipped aircraft and vehicles. ASTA-2 also includes initial functionality for an integrated traffic-management system designed to reduce delays, improve airport capacity, and reduce controller workload intensity. ASTA-3 adds a two-way digital data link between tower and cockpit as part of the surface Mode-S capability. This link makes possible a number of safety and traffic-management functions, including automatic direct cockpit alerts, automatic taxi guidance and monitoring, delivery of surface traffic information to pilots to reduce movement errors, delivery of information on potentially hazardous weather, and error-free transmission of flight-route clearance data.

Surface Surveillance

The control of traffic from the tower is based on three major components: (1) surveillance to determine the traffic situation, (2) processing to formulate a plan for managing the traffic, and (3) communications to issue clearances to implement that plan. The ASTA program provides additional tools to the controller in all three of these areas.

Electronic Surveillance

The primary mission of air traffic controllers is to insure safety, and safety depends on adequate physical separation between all airborne and surface traffic. A controller achieves separation through the use of surveillance, either electronically by radar or visually by direct observation. For the en-route or terminal-area controller, electronic surveillance is the only surveillance available. Although most air traffic can be detected by primary radar, which relies on simple skin reflections, the trend is to place a greater reliance on beacon radar.

Beacon radar, which is also known as the Air Traffic Control Radio Beacon System (ATCRBS), is based on the concept of equipping cooperating targets with a transponder. The transponder receives interrogation pulses from a beacon radar and emits a reply containing (as a minimum) a 4-digit octal transponder code entered by

COMMUNICATIONS AND TRAGEDY

ON 3 DECEMBER 1990, at Detroit's Metropolitan Airport, the cockpit crew of a Northwest Airlines DC-9 taxiing for takeoff became lost in heavy ground fog and blundered onto an active runway. Seconds later, the right wing of a Northwest Airlines 727, which was attempting to take off on that runway, struck the fuselage of the DC-9, which immediately burst into flames. The tragic result was eight dead and 22 injured. The following communications, taken from the National Transportation Safety Board (NTSB) official transcript of the tower tape, illustrate the rapid-fire nature of ATC surface communications and the difficulty tower controllers face in monitoring traffic when low visibility conditions exist and no surface radar is present.

In the following communication, GC-E is the ground controller responsible for the eastern portion of the airport, and NWA1482 is the cockpit crew of the DC-9. Times are in Universal Coordinated Time and communications with other aircraft during this period have been omitted. Although the NTSB transcript contains neither punctuation nor explanatory notes, we annotate this communication for clarity. Explanatory notes are italicized and enclosed in brackets. The following are taxiway names: inner, outer, oscar six, oscar five, oscar four, fox (or foxtrot), and xray. The runways are 9 or 27 (the same runway in opposite directions, referred to below as "niner two seven") and 3 Center or 21 Center (the same runway in opposite directions).

Time	*Source*	*Message*
1837:05	GC-E	Northwest fourteen eighty-two, ground, are you on? *[the ground controller is asking the DC-9 crew if they are listening on the ground controller's frequency.]*
1837:07	NWA1482	Yes, go ahead.
1837:08	GC-E	Yeah, what's your position?
1837:09	NWA1482	We're by the fire station.
1837:10	GC-E	Roger, Northwest fourteen eighty-two, taxi inner oscar six fox report making the, uh, right turn on xray. *[the controller is saying to use taxiways oscar six, fox, and then turn right on taxiway xray]*
1837:18	NWA1482	Inner oscar six to foxtrot report xray. *[The DC-9 crew is reading back the clearance to confirm its accuracy]*
1839:37	GC-E	Northwest fourteen eighty-two, what's your position now?
1839:40	NWA1482	Uh, we're, uh, approaching the parallel runway on oscar six.
1839:49	GC-E	You're approaching oscar six on runway niner two seven?
1839:53	NWA1482	We're headed eastbound on oscar six here.
1840:02	GC-E	Northwest fourteen eighty-two, report crossing runway niner two seven on fox.

Time	*Source*	*Message*
1840:06	NWA1482	Okay, I think we might have missed oscar six. I see a sign here that says I've got an arrow fox oscar five. I think we're on foxtrot now. *[They were not.]*
1840:17	GC-E	Northwest fourteen eighty-two, ah, you just approach oscar five and you are on the outer?
1840:24	NWA1482	Yeah, that's right.
1840:25	GC-E	Northwest fourteen eighty-two, continue to oscar four then turn right on xray. Continue via xray to three center.
1840:32	NWA1482	Xray, roger.
1840:40	GC-E	Northwest fourteen eighty-two, ah, report approaching xray and fox.
1841:05	GC-E	Northwest fourteen eighty-two, at oscar four make the right turn on xray and then report crossing nine two seven.
1841:11	NWA1482	Roger, at oscar four make a right turn on xray.
1841:37	NWA1482	And, ground, uh, fourteen eighty-two, did you say we were cleared to cross two seven and nine?
1841:41	GC-E	Northwest fourteen eighty-two, affirmative, cross nine two seven.
1841:44	NWA1482	Roger.
1841:51	GC-E	Northwest fourteen eighty-two, when you get to fox and xray, follow a Mesaba Fokker that'll be approaching from your right side. *[Mesaba is a regional airline; Fokker refers to a type of airplane manufactured in Germany]*
1841:58	NWA1482	Okay, fourteen eighty-two. *[The DC-9 crew is acknowledging the clearance to follow the other plane]*
1843:46	GC-E	Northwest fourteen eighty-two, ground, say your position.
1843:49	NWA1482	Ah, I believe we're at the intersection of xray and, ah, nine two seven.
1843:58	GC-E	Xray and nine two seven, okay, are you a southbound?
1844:02	NWA1482	Yeah, we're holding short of nine two seven here right now.
1844:05	GC-E	Cross nine two seven, Northwest fourteen eighty-two, taxi via xray to three center.
1844:18	GC-E	Northwest fourteen eighty-two, did you copy?
1844:20	NWA1482	Yes.
1844:57	GC-E	And, Northwest fourteen eighty-two, just to verify you are proceeding southbound on xray now, you're across nine two seven.

Time	*Source*	*Message*
1845:02	NWA1482	Ah, we're not sure, it's so foggy out here, we're completely stuck here. *[At this point, the DC-9 had taxied onto the runway being used by the 727 for takeoff]*
1845:05	GC-E	Okay, are you on a taxiway or a runway or where?
1845:08	NWA1482	Runway. We're right by zero four.
1845:12	GC-E	Okay, ah, Northwest fourteen eighty-two, roger, are you clear of runway three center?
1845:18	NWA1482	It looks like we're on two one center here. *[21 center and 3 center are the same runway in opposite directions. At this point the DC-9 crew knew that the pavement beneath them was not a taxiway.]*
1845:27	GC-E	Northwest fourteen eighty-two, you say you're on runway two one center?
1845:30	NWA1482	Believe we are, we're not sure.
1845:33	GC-E	Northwest fourteen eighty-two, roger, if you're on two one center exit that runway immediately, sir!

Seven seconds after this communication the accident occurred. Ironically, the 727 cockpit crew was communicating with the same ground controller when the DC-9 crew became lost, and thus overheard most of the exchanges. Following the NWA1482 transmission at 1840:06 when the DC-9 pilot said they had missed taxiway oscar six and thought they were on foxtrot (taxiway fox), the cockpit voice recorder in the 727 captured an inter-cockpit exchange in which the pilot said, "He sure did" (i.e., miss oscar six) and the copilot added, "I don't think so" (i.e., the DC-9 was on foxtrot now; it wasn't).

the pilot. The three types of ATCRBS transponders now in use are Mode A (the oldest and most basic), Mode C, and Mode S (the most advanced). In addition to the identity code, Mode-C and Mode-S units also send the pressure altitude, and Mode S adds a Mode-S address that uniquely identifies the individual aircraft. Mode S also provides a two-way digital data link between ground and cockpit; this data link can be used for a number of communications purposes.

All traffic at major domestic airports is required to be equipped with either Mode C or Mode S (a small but decreasing number of aircraft still use Mode A). Over the next few years, Mode S transponders will be installed in all transport aircraft with more than 30 seats, as part of an FAA-imposed requirement for a collision-avoidance system. One feature of the Mode-S system that greatly increases surveillance capacity is the ability to interrogate selectively any single aircraft within a crowded airspace.

Although Mode S is basically a surveillance system, like Mode A and Mode C, the additional availability of the digital data link will have significant impact on air traffic control in the years ahead. As suitable cockpit and ground equipment becomes available, the data link will permit advances such as the substitution of electronic messages for voice traffic and the automatic delivery of in-flight weather, heading, airspeed, and other data from the aircraft to ATC control centers. In the future, ATC

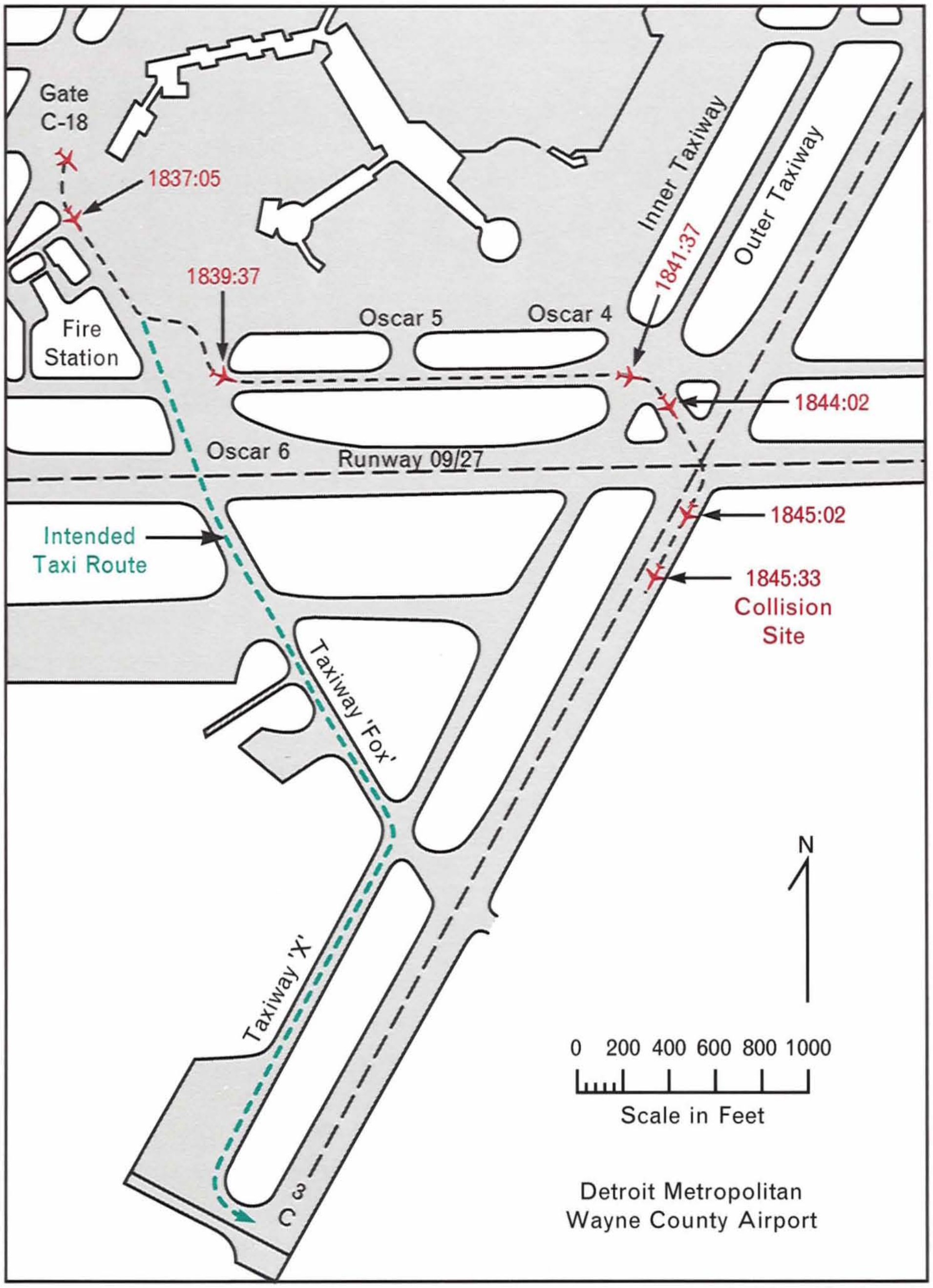


FIGURE A. The taxi route of Northwest Airlines DC-9 flight 1482 at Detroit Metropolitan Wayne County Airport on 3 December 1990. The intended taxi route is shown in color. The aircraft became lost in dense fog and blundered into the path of a departing Northwest 727 jet. Eight people died and 22 were injured in the accident. (Airport map and reconstruction of time and position courtesy of the National Transportation Safety Board.)

clearances involving altitude, heading, and speed could also be transmitted directly to the flight data computer in the cockpit for execution without the need for human intervention.

Existing Radar Surveillance Techniques

Because of the difficulty of monitoring the airport surface during periods of low visibility, many people often assume that surface radar is common at most airports. In fact, only 12 domestic airports currently have a surface radar, which is known as the Airport Surface Detection Equipment (ASDE-2) radar. This vacuum-tube unit, first installed in the 1960s, is limited by clutter, low reliability, and unavailability of spare parts. Two airports, Los Angeles International and Anchorage International, have one-of-a-kind solid state units that improve performance somewhat compared to the ASDE-2, although the Los Angeles radar is essentially worn out and thus frequently out of service. It was not in service at the time of the surface accident in February 1991.

Although en-route and terminal-area controllers depend on electronic surveillance to monitor aircraft, the tower controller relies almost completely on visual techniques to monitor the airport surface and the approach airspace. In other words, the controller looks out of the tower window to observe the aircraft and vehicles within the movement area and on approach. This method can provide excellent surveillance only in conditions of good visibility. At night or in the presence of haze, fog, or low ceilings, a controller must rely on nonvisual methods to maintain situational awareness. Because few domestic airports today have a surface radar, the controller typically locates surface traffic by a time-consuming series of "where are you" queries over voice radio. The task of surveillance is further complicated at heavily used hub airports where periods of peak traffic (called a *push*) are characterized by lines of essentially identical aircraft bearing common markings.

While the ground controller concentrates completely on surface traffic, the local controller must maintain awareness of aircraft both on the ground and in the airspace that surrounds the airport. For surveillance of the surrounding airspace, the local controller uses a display system called a Bright Radar Indicator Tower Equipment (BRITE). The surveillance data shown on the BRITE originates in an airport surveillance radar (ASR) such as the ASR-7 or ASR-9. From there it passes to the Automated Radar Terminal System (ARTS) computer in the associated TRACON, and then on to the tower BRITE via a dedicated display channel.

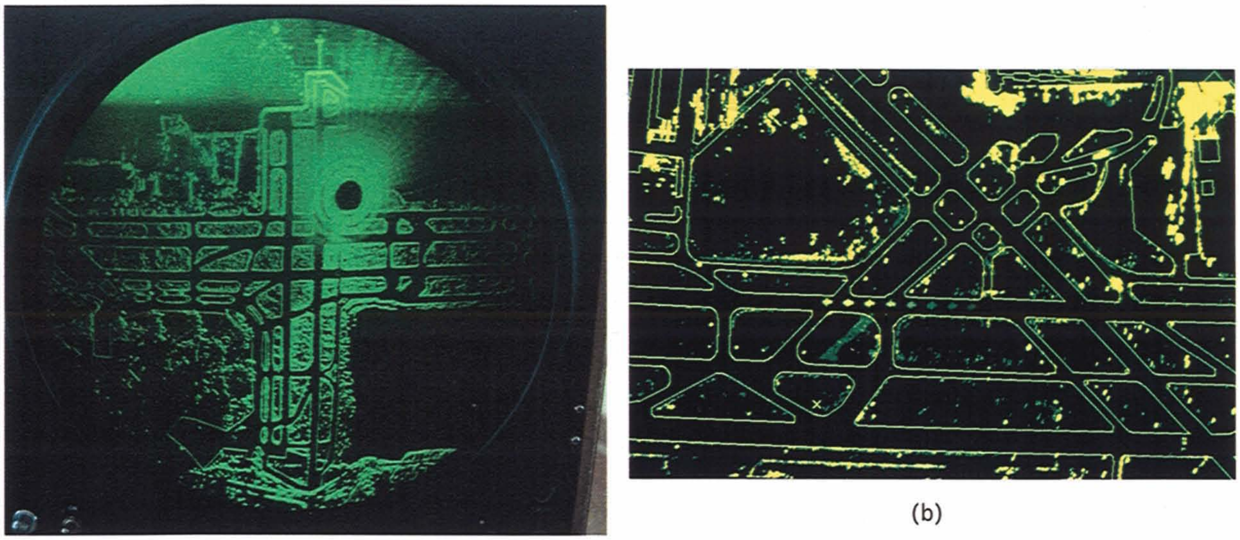
Advanced Surface Radar—the ASDE-3

Because effective visual surveillance of the airport surface is possible most of the time, the development of modern radar for surface surveillance has lagged far behind developments in terminal radar and en-route radar. Within the next few years, however, the old ASDE-2 units will be replaced by a new surface radar known as the ASDE-3. At the present time, 29 major domestic airports are scheduled to receive the ASDE-3, and six to 10 additional airports are under consideration. This radar, which is designed to operate 24 hours a day, employs frequency agility and circular polarization to achieve a significant improvement in performance during heavy rain. It also utilizes clutter reduction techniques to minimize distracting false targets. Figure 4, which shows display screens from both the ASDE-2 and ASDE-3 radars, illustrates the dramatic improvement in image quality with the new unit.

The first method of automatic surveillance included in the ASTA program is the use of ASDE-3 radar data to produce target reports that can be processed by safety algorithms in an external computer. Additional data are obtained from the ASR through an interface to the ARTS computer located in the TRACON. The required data include coverage of the final approach paths out to a distance of approximately five nmi (a nautical mile is 1.15 statute miles, or 6076 ft, or 1.85 km). This technique is now being implemented by the AMASS program, which represents an early version of an automatic alerting system. AMASS will detect most runway incursions and provide audible alerts for tower controllers. The system also includes ASDE-3 display enhancements designed to assist the controller in quickly recognizing the traffic situation following an alert. AMASS will be implemented at the ASDE-3 sites starting in 1995 by the Norden Systems Division of United Technologies.

Mode-S Beacon Surface Surveillance

The ASDE-3 radar displays all targets that can be detected by primary surface radar out to 4 nmi in range and up to approximately 200 ft in elevation, but it does not identify the aircraft or distinguish between airborne and surface targets or clutter. To identify aircraft, and for reasons of redundancy and improved accuracy, the ASTA system will employ a second surveillance technique. This



(a) (b)

FIGURE 4. Airport Surface Detection Equipment (ASDE) radar displays: (a) This photograph of the display of the ASDE-2 radar at San Francisco's International Airport shows the high degree of clutter common to these older surface radars in use at 12 U.S. airports. The circular hole in the image represents the location of the radar antenna. Paved airport areas such as runways, taxiways, and ramp areas are relatively free of clutter returns, which fortunately aids controllers in locating traffic on the airport. The clutter in all regions increases dramatically during rainfall, however, which renders the ASDE-2 radar all but useless. (b) The new ASDE-3 solid state radar employs frequency agility and circular polarization to improve performance significantly during heavy rainfall. In addition, the ASDE-3 reduces clutter in off-pavement areas of the display by introducing higher thresholds below which the image is suppressed. The radar image shown here is from the first ASDE-3 radar delivered to a major airport (Pittsburgh) and was recorded prior to the selection of final clutter thresholds. As a result, the image shows an abnormal amount of off-pavement clutter, which will be significantly reduced before the unit is commissioned late in 1991.

second technique extends the Mode-S beacon system, which is now being implemented for en-route and terminal surveillance, to the airport surface. In contrast to the complex Mode-S sensors required for airborne surveillance, however, the surface Mode-S beacon system typically consists of a set of five to seven simple stationary antennas and associated electronics located around the periphery of the airport.

The Mode-S transponder on an aircraft not only replies to ATC interrogation, it also spontaneously emits a signal called a *squitter* once per second. The purpose of this signal is to assist Mode-S sensors in acquiring airborne aircraft. Fortunately, it will also allow a surface Mode-S system to determine the location of the aircraft on the ground by observing the differences in arrival time of the signal at three or more stationary sensors. This technique, which is illustrated in Figure 5, is called *time-difference multilateration* and is expected to provide surveillance of comparable accuracy to that possible with the primary ASDE-3 radar. The combination of the ASDE-3 and Mode-S multilateration will provide more reliable surface surveillance than either could provide alone, along with a method of placing aircraft identification information on the ASDE-3 display.

Other Surveillance Techniques

In the 1940s and early 1950s, no network of ATC radars existed to provide en-route and terminal surveillance for domestic aviation. As a result, air traffic controllers were forced to rely solely on position reports from pilots for surveillance. Separation was accomplished by a *block-control* system (essentially the same system used by railroads) with paper flight-progress strips used to record current position. Given the light traffic volume of the day, this system worked well; that is, until 30 June 1956, when a United Airlines DC-7 collided with a TWA

Lockheed Constellation over the Grand Canyon. That event marked the beginning of an effort to implement a nationwide network of surveillance radars. Primary (skin return) radar was used initially with the face of the radar display mounted horizontally. The horizontal display surface allowed controllers to tag aircraft returns directly on the display by using small wooden boat-shaped tokens bearing a slip of paper inscribed with the flight identification number. As each new position report came in, the controller would push the corresponding flight's token, usually referred to as a *shrimp boat*, along the reported path. This system of identifying flights on the en-route radar display was replaced in the mid-1960s when beacon radar came into use. The transponder code assigned to each flight allowed a identification tag to be added to the radar display, without human intervention or opportunity for error.

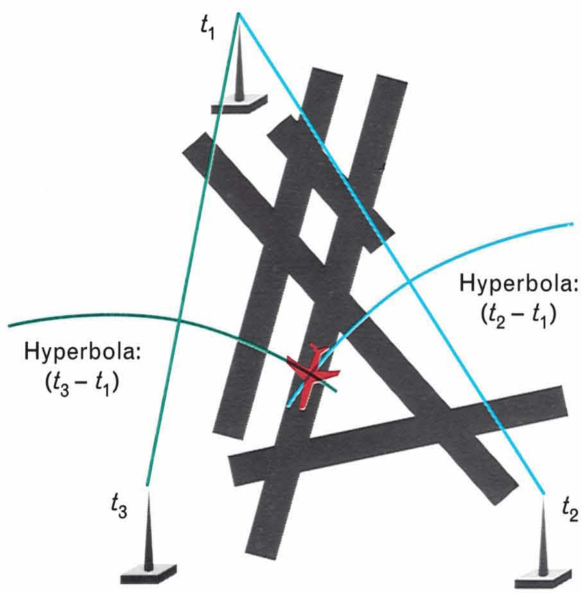


FIGURE 5. Surveillance by time-difference multilateration. This method of surveillance precisely determines the time of arrival at a receiver site of a signal emitted by equipment on the aircraft. For each pair of fixed receiver sites, a given time-of-arrival difference corresponds to a hyperbolic curve, as illustrated above. For surface applications, good signal reception by three receiver sites for a particular aircraft position allows the aircraft to be located at the intersection of two hyperbolas. In the ASTA program the multilateration system will have five to seven receiver sites with omnidirectional antennas. The signal from the aircraft will be the squitter signal emitted once per second by the Mode-S transponder.

Radar coverage over the continental U.S. is now mostly complete, but no comparable radar surveillance exists for air routes over the ocean. As a consequence, U.S. and foreign controllers insure safety by using in-trail spacings of up to 20 minutes (approximately 150 nmi) between aircraft. To improve capacity by reducing spacing both in trail and laterally, the FAA is developing a system that is a form of automated dependent surveillance (ADS). This system combines an accurate navigation system with a digital data link to permit the automatic reporting of positions to ATC. The navigation system of choice for transoceanic ADS is the satellite-based Global Positioning System (GPS); the data link is a digital channel sent through commercial communications satellites. When transoceanic ADS is fully operational, separation standards may be reduced significantly. This reduction in separation will improve capacity as well as permit airlines to optimize the route for each flight more effectively based on prevailing winds and temperatures aloft.

The principal of ADS can also be employed in airport surface applications. At present, however, no suitable combination of precision surface navigation and high-capacity digital data link has been developed. Many in the aviation community are convinced that a precision navigation system known as *differential GPS* will lead to the development of new instrument-approach procedures. Differential GPS uses a GPS receiver at a fixed ground location on or near the airport. The function of the ground receiver is to determine (at each second) the errors in apparent position by using the GPS signals from the satellites in view. By broadcasting these errors to all aircraft in the vicinity, the differential GPS system could permit approaches providing both lateral and vertical guidance with an accuracy corresponding to present techniques for *precision* approaches. Because the FAA in the past has required independence between the lateral and vertical components of the system, however, it is not clear to what extent differential GPS will be allowed to supplement, or even replace, existing precision approaches.

Nonprecision approaches, which provide no vertical guidance, will be possible with GPS even without the differential feature, even if the Department of Defense (DoD) activates the *selective availability* feature of GPS. (Selective availability, when turned on by the DoD, reduces the positional accuracy of the GPS system for nonmilitary users, thereby denying potential enemies or terrorists a source of precise navigation.) Other surveillance and navigation options in addition to differential GPS have been proposed for the airport surface. These options are summarized in Tables 1 and 2.

A surface automation system based in part on the availability of electronic surveillance must employ surveillance techniques that provide full coverage of the movement area rather than only point surveillance. Most automation concepts based on point surveillance, such as buried loops or various scanner techniques, are variations of the railroad industry's block-control system. For airport applications, these techniques develop problems when surface-traffic density increases to the point at which the aircraft spacing is on the order of the block size. Furthermore, the presence of large aircraft such as a Boeing 747-400 (232 ft long) calls for blocks on the order of 300 ft in extent, a distance that will easily hold several small commuter or general-aviation aircraft. The presence of multiple targets within a single block renders block-control systems ineffective. In other words, safety or capacity systems based on point surveillance (as opposed to area surveillance) have problems when they are needed the most—when traffic density is high. For this reason, the ASTA concept combines two methods of

Table 1. Surface Surveillance Techniques

Technique	*Type*	*Provides ID?*	*Uses Existing Equipment?*	*Comments*
Primary Radar	Full Area	No	Yes	ASDE-3 Is an Example
Multilateration	Full Area	Yes	Yes[1]	Mode S and ATCRBS
Transponder Interrogation #1[2]	Full Area	Yes	Yes[3]	Problems with High Traffic Density
Acoustic (Active)	Small Area	No	Yes	Technology Not Available
Acoustic (Passive)	Small Area	No	Yes	Problem with Quiet Targets
Infrared	Small Area	No	Yes	Short Range in Wet Fog
Buried Loops	Point	No[4]	Yes[4]	Expensive to Install
Radio Frequency Identification[5]	Point	Yes	No	Range Is a Few Hundred Feet
Transponder Interrogation #2[6]	Point	Yes	No[7]	In Use Overseas?
Bar Code Scanner	Point	Yes	No	Short Range; Eye-Safety Issue[8]

1. Existing equipage requires some modification to handle ATCRBS surface targets.
2. Area surveillance of ATCRBS targets is based on intersecting pencil beams from electronically scanned antennas, and these antennas are expensive.
3. Existing equipage requires some modification.
4. Techniques are available for positive ID with buried loops if new equipage is permitted. Basic buried-loop techniques give presence/absence only.
5. Radio-frequency identification systems have limited range (a few hundred feet) and require a line-of-sight path for the interrogation beam. A longer range is possible, but a steerable pencil beam would be required to monitor a significant area.
6. Point interrogation by a low-power beam from a stationary directional antenna.
7. Requires a modification to the Mode-A and Mode-C transponders to reduce reply power on ground, and a change in operational procedure to leave the transponder active while the aircraft is on the airport surface.
8. Long-range (e.g., 2000 to 6000 ft) scanners, which would be usable only in good visibility, require a high-power laser that introduces an eye-safety hazard for cockpit crews.

Table 2. Surface Navigation Techniques

Technique	*Type*	*Equipage Issue?*	*Comments*
Precision Distance Measuring Equipment (PDME)[1]	Full Area	Yes	Component of Microwave Landing System
Inverse Multilateration[2]	Full Area	Yes	
Differential Global Positioning System	Full Area	Yes	Popular Option
Differential LORAN-C[3]	Full Area	Yes	Based on LORAN-C

1. Multiple PDME ground stations would be located around the airport to permit aircraft to determine position by triangulation.
2. Multiple stationary emitters on the airport surface permit determination of aircraft position by triangulation or multilateration.
3. The Long Range Navigation (LORAN-C) System is based on a marine navigation system consisting of chains of high-power low-frequency transmitters. Each chain, which consists of one master station and three to four slave stations, can cover an area on the order of 1000 nmi in extent.

area surveillance: the ASDE-3 primary radar and the Mode-S beacon multilateration system.

Processing and Surface Communications

A controller performs complex mental gymnastics to process surface-traffic information. The controller must not only constantly determine the status of the traffic but must repeatedly reformulate a plan consistent with overall traffic objectives and then execute that plan while coordinating with other controllers. The flow chart shown in Figure 6 describes this activity, although the process is not always as simple or as ordered as the chart implies. Figure 6 also lists some of the automation possibilities that can assist the controller in the required task at each step of the process. The objective of the automation is to improve human performance while keeping responsibility for the control of surface operations firmly in the hands of the controller.

Voice Channels

Communications between tower and cockpit are currently accomplished by using one of many VHF voice channels. Each ground and local controller, as well as certain other tower positions, uses a specific VHF frequency that varies from tower to tower to avoid interference. Table 3 shows the list of frequencies for a typical large airport such as Chicago's O'Hare International. Despite the large number of frequencies—18 at O'Hare—voice communications at times limit the capacity of larger airports. Figure 7 illustrates usage data for the most critical voice frequencies (the two channels used by ground controllers) at O'Hare. During periods of reduced visibility and high traffic, the use of the voice channel often exceeds the level that represents effective saturation.

The voice channels allow the controller to issue clearances and the pilot to respond; in the absence of surface radar they also provide a secondary method of surveillance. In other words, without suitable radar or other surveillance, the controllers are often forced to ask the pilots, "Where are you?" These surveillance communications significantly contribute to channel overload and reduced airport capacity. The implementation of automatic methods of communication, in particular a two-way tower-to-cockpit digital data link, promises to reduce this problem.

Advanced Tower-to-Cockpit Communications

The air traffic control system in use today depends heavily on verbal communications. This dependence, which applies equally to the control of surface traffic and to airborne traffic, not only introduces errors, it can at times restrict capacity. To address these problems, future sur-

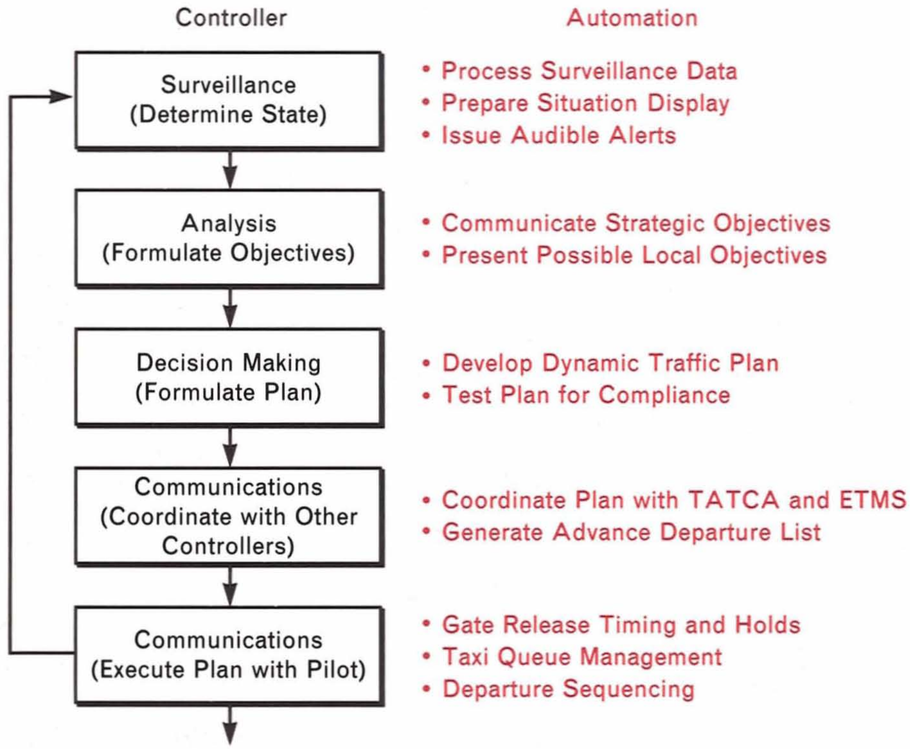


FIGURE 6. The tower-controller processing loop. This diagram summarizes the complex sequence of tasks performed by a tower controller in managing airport traffic. In practice, the controller is at a different point in the loop for each of the aircraft under his or her control. The role of the system designer is to develop ways for the automation to aid the controller in the surveillance, analysis, decision-making, and communications steps. Some automation possibilities for each step in the sequence are listed on the right.

face communications systems will supplement verbal exchanges with digital data-link communications between tower and cockpit. For example, the traffic-management automation system in phase 3 of the ASTA system will suggest taxi routes for departing aircraft. The controller will approve the suggestion either by pressing an appropriate button or, in an advanced version, through a speaker-dependent voice-recognition system. The traffic-management automation system will then transmit the approved taxi route to the cockpit by the digital data link. The system could also transmit other instructions to the cockpit, such as where to turn or stop, and monitor the aircraft's progress for compliance. Comparable services could be provided for arriving aircraft. The benefits of such a system will include a significant reduction in voice traffic and a corresponding decrease in movement errors on the surface.

Automated Clearance Delivery

With few exceptions, almost all airline and other commercial flights are required to operate under positive air traffic control. This requirement includes all flights higher than 18,000 ft above mean sea level and during periods when ceiling and visibility conditions call for flight under instrument flight rules. For each flight, the pilot or airline is required to file a flight plan either with one of the FAA's Flight Service Stations or directly with an en-route center's host computer (commercial airlines employ a telephone-based data link to file directly with the center computer).

After a flight plan is filed, the first verbal contact with tower controllers prior to departure is a call by the pilot (or copilot) on the clearance-delivery frequency to obtain the final flight-route clearance and any additional data

Table 3. Airport Communication Frequencies at O'Hare International Airport

Frequencies (MHz)	*Air Traffic Control Function*
135.4	Airport Terminal Information Service[1]
119.0, 125.7, 124.35 128.45, and 121.15	TRACON Approach Control
125.0, 125.4, and 127.4	TRACON Departure Control
126.9	Tower (North Local Controller)
120.75	Tower (South Local Controller)
126.2	Tower
121.9	Ground Control (Inbound)
121.75	Ground Control (Outbound)
121.675	Ground Metering
121.6 and 119.25	Pre-Taxi and Clearance Delivery
122.95	UNICOM (Fuel and Services)

1. Recorded airport status information on weather, runway configuration, obstructions, and other data that can assist pilots in operating safely and efficiently at the airport.

related to the flight (such as a gate hold). The call to clearance delivery confirms that the flight will proceed and determines if any changes in the planned route have been imposed by ATC. Additional details include an initial assigned altitude, a squawk code for the transponder, a departure frequency, and any other special information related to the clearance. Usually the clearance-delivery controller reads the clearance to the flight crew, who then write down any variation from the route requested, along with the additional data. The pilot then reads back the clearance to confirm its accuracy.

Because the verbal-delivery and read-back process is both time consuming and error prone, the FAA has joined with a number of airlines in testing a system to transmit predeparture clearances via a two-way digital data link. This VHF link, which is operated by the airline-owned ARINC company (formerly Aeronautical Radio, Incorporated), is called the Aircraft Communications Addressing and Reporting System (ACARS). After allowing for inefficiencies due to access protocols and other factors, the ACARS link can transmit data at an average of 300 to 600 bits/sec. Following a successful test period (which is now complete), the FAA and major airlines have joined in partnership to implement this automatic clearance-delivery system within the next few years at 15 to 20 major domestic airports. This partnership is unusual because the FAA has chosen a system not under its direct control for the delivery of ATC data.

In the future, ARINC will implement a new digital data link called the Aviation Packet Network. This link will be fully compatible with the Open Systems Interconnection reference model that has been adopted for the Aeronautical Telecommunications Network. The major benefit of the Aviation Packet Network and the Open Systems Interconnection model is that the user need not be concerned with the choice of transmission medium or route. In general, the communications system at the source will select a medium and route for each packet, based on the status of the network at the instant the packet is ready for transmission. At the final destination, the multiple packets will be collected and reassembled into the original message and then delivered to the recipient's communications system. The Aviation Packet Network link is not an FAA system, however; it is intended for use by the airlines in the transmission of

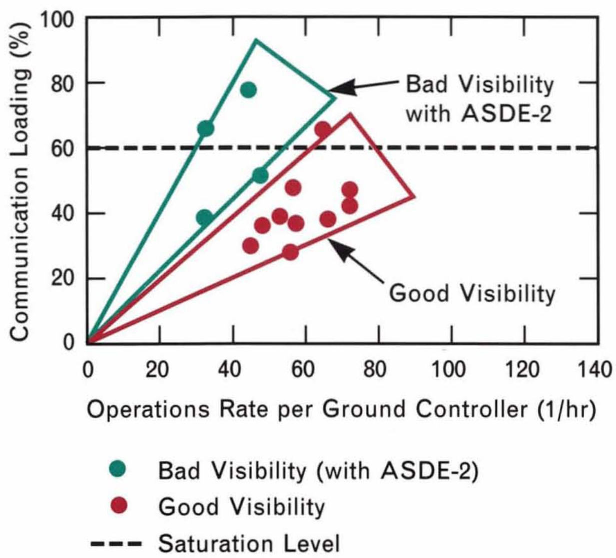


FIGURE 7. Voice-channel loading at O'Hare International Airport. The use of voice communications to deliver clearances, or movement instructions, from the control tower to the cockpit represents a potential bottleneck to the improvement of airport capacity. O'Hare's capacity is often limited by overloading on the frequencies used by the two ground controllers responsible for all taxiing aircraft and vehicles within the movement area. During periods of poor visibility, use of the voice channel can climb above the 60% level that represents effective saturation.

schedule, maintenance, and other operations data. The Aviation Packet Network could eventually replace ACARS as a method of delivering flight route clearances from ATC to cockpits, but no plans currently exist for this change.

The ASTA Mode-S Two-Way Digital Data Link

ACARS has demonstrated the benefits of a digital data link between tower and cockpit to deliver flight route clearances. Because this application only begins to solve the problem, however, additional data-link capacity is highly desirable. Applications that reduce loading on the frequencies of the ground controller and local controller must also be implemented as part of tower automation. In the ASTA program, reduced loading will occur because of the extension of the Mode-S beacon surveillance system to the airport surface.

For aircraft on the airport surface and within the movement area, the Mode-S link permits a data rate of approximately 100,000 bits/sec (this high data rate is possible in part because of the use of nonrotating antennas). This capacity will support the transmission of ATC clearances such as taxi routing, flight route clearances, weather information, and other applications.

The suitability of a digital data link on the airport surface depends in part on the match between the available data rate and the applications the data link must serve. Potential applications for a data link include the delivery of predeparture clearances (described earlier), the predeparture delivery of weather data to the cockpit, and the automatic reporting to ATC of aircraft position on the airport surface. Table 4 lists the approximate data rates required for these and similar applications. (These data rates are based on the assumptions shown in the table, and are not necessarily representative of candidate designs.) Reduced data rates might be obtained through the use of alternative reporting formats, alternative link protocols, and compression techniques.

Tower Control Computer Complex

A component of the AAS that impacts the tower controller strongly is the Tower Control Computer Complex (TCCC). The TCCC, when it becomes available in the late 1990s, will be located in the control tower, and is based on an IBM PowerStation 6000 workstation computer with an Ethernet local-area network and communications links to TRACON and en-route control center computers. Current plans for the implementation of the AAS indicate that TCCC systems will be installed in from 150 to 260 control towers, starting with the busiest airports.

In its initial form, the functionality in the TCCC will provide an electronic flight-strip system that will replace the manual system of paper flight strips in plastic holders [5]. The development of TCCC equipment for the tower is complicated, however, by a fundamental conflict in surveillance activity. The primary responsibility of ground and local controllers is to observe surface traffic by looking out the window; this task is not compatible with operating a keyboard and trackball while monitoring a computer screen. Even though these compatibility issues are not yet resolved, the integration of ASTA functionality into the TCCC environment is an important goal of the ASTA program.

The ASTA Processor

The implementation of a comprehensive and advanced automation system such as ASTA is made possible in part by the dramatic advances in computational power that have occurred in the 1980s. The ASTA system will require one or more processors with a combined power that in the mid-1980s was available only from a mainframe computer. This level of computing power is now available from workstation-class machines such as the IBM PowerStation 6000, which will be used in the TCCC system. Fortunately for ASTA, the architecture of TCCC employs a high-speed token-ring network. Additional computational power to accommodate ASTA functionality can be obtained through the addition of another processor to the TCCC network; this approach offers significant advantages in logistics and maintenance.

The computational load represented by the ASTA system can be divided into separate processes that implement the surveillance, safety, and traffic-management systems. For surveillance, the automation processing includes the extraction and formatting of raw radar data in digital form, the suppression of clutter, and the acquisi-

Table 4. Hypothetical Data Rates for Tower/Cockpit Applications

Application	*Peak Data Rate (bits/sec)*	*Assumptions*[1]
Clearance Delivery (Flight Plans)	50	• 100 Bytes per Flight Plan • 120 Departures per Hour
Delivery of Taxi Clearances	50	• 50 Bytes per Clearance • 120 Departures per Hour • 120 Arrivals per Hour
Airborne Position Reporting (Transoceanic)	60	• 200 Aircraft • 100 Bits per Report • 1 Report per 10 Minutes
Active Taxi-Route Guidance	100	• 25 Bytes per Message • 120 Departures per Hour • 120 Arrivals per Hour • 4 Messages per Aircraft
Direct Cockpit Alerts	400	• 50 Bytes per Alert • Maximum Delivery Time of 1 Second
Delivery of Weather Maps to the Cockpit (Broadcast Mode)	1300	• 64 × 64 Map Pixels • 8 Bits per Pixel • 10 Seconds per Map (Maximum) • Compression Factor of 5
Automated Dependent Surveillance	20,000	• 100 Targets[2] • 100 Bits per Report • 1 Report per Second per Target
Delivery of Surface Traffic Data to the Cockpit	40,000	• 40 Receiving Aircraft • 5 Targets per Report • 100 Bits per Target • 1 Report per Second

1. All assumptions include 50% channel efficiency.
2. Aircraft plus vehicles within the movement area.

tion of targets, along with centroiding and scan-to-scan correlation. In addition, the data originating in the ASR and obtained through a tap to the ARTS computer must be filtered to identify aircraft that are approaching the airport to land. Finally, algorithms that allow targets to coast through coverage gaps must be implemented, and the ARTS data must be correlated with ASDE data to accommodate areas of overlapping coverage.

Processes in the safety system include the estimation of target trajectories (to predict future conflicts), the safety and alerting algorithms, the light-control algorithms, and the implementation of graphical and textual enhancements on the ASDE display. For the traffic-management system, ASTA must interface with the electronic flight-progress system (electronic flight strips) from the TCCC, and implement a central traffic planner plus a number of other automation aids designed to interface both the plan and the coordination functions with the controller. In all cases, the automation must be designed to aid rather than replace the skills and functions of the human controller.

The Architecture of ASTA

Figure 8 illustrates the architecture of the ASTA system. The ASDE-3 surface radar, with its characteristic rotodome on top of the tower cab, provides the initial data for the automatic surveillance of the movement area. The surface version of the Mode-S beacon system, which contains three or more simple sensors, supplements this surveillance and provides the positive identification required to show data tags on the ASDE-3 display. Additional ASTA elements include the runway-status lights and the ASTA processing facility located in the tower below the cab.

Technological Foundations of ASTA

The technological foundations for tower automation include elements of electronic surveillance, communications, and automation processing, with the addition of human elements such as the interface between the automation system and the controller. Table 5 provides an expanded listing of five significant areas of development for tower automation. These areas are (1) electronic surveillance to provide target identity and track data to the safety and traffic-management systems, (2) electronic communications to reduce errors and unload voice channels, (3) a safety system including safety algorithms and automatic surface lights, (4) a traffic-management system integrated into other ATC traffic automation systems, and (5) human factors.

We can view the components of a tower automation system from two vantage points. On one hand, the engineer concentrates on the technology that must be developed and installed to implement the system. For ASTA this technology includes the electronic area surveillance, the electronic communications capability, the safety and traffic-management algorithms, and the automatically controlled surface lights. On the other hand, the controller focuses on the specific products that affect his or her workload and effectiveness. These products include equipment such as a surveillance display, or functional capabilities such as data tags inserted on the display to identify aircraft. In the following sections we examine ASTA from the point of view of both the technology and the products. Table 6 lists the products provided to tower controllers by ASTA and preceding programs, including the early implementation represented by AMASS. The table also indicates the degree of safety benefit and capacity benefit of the product.

Surface Mode-S System

An important element in the ASTA concept is the extension of Mode-S beacon-radar surveillance to the airport surface. This extension removes an arbitrary boundary between the predeparture and postdeparture phases of flight. It also yields two important assets, which are the positive identification of aircraft and the availability of a two-way tower-to-cockpit digital data link. Because ten years may pass before all aircraft operating at major airports are equipped with Mode-S transponders, we must consider using the Mode-S surface-surveillance system to monitor and identify Mode-A and Mode-C aircraft. Fortunately, a method requiring relatively low-cost additional equipage for Mode-A and Mode-C aircraft will permit the Mode-S system to track and identify these aircraft. Thus all aircraft will be identified automatically, and aircraft data tags can be added to the ASDE-3 surface radar display.

The benefits of the two-way digital data link include the automatic transmission of flight-route clearances and graphical weather data. The data link also provides two

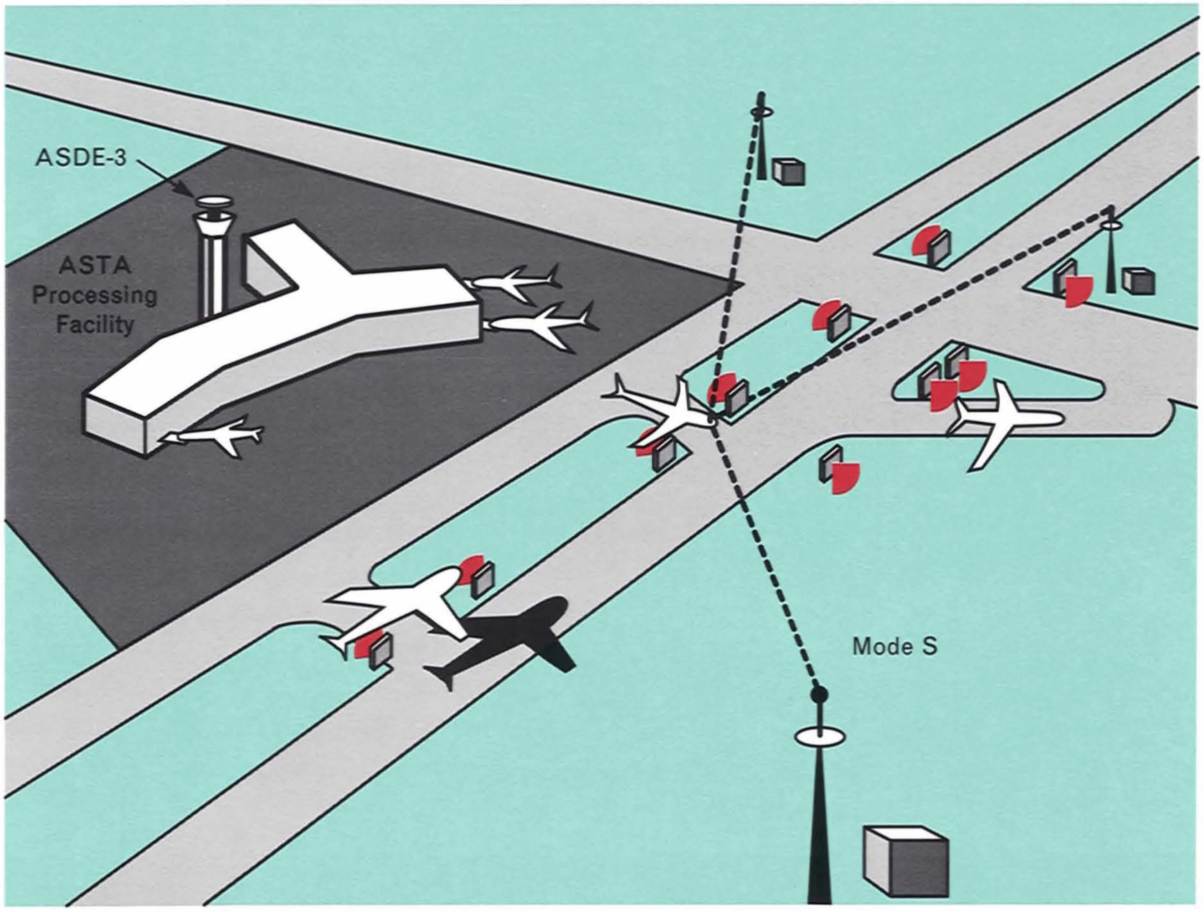


FIGURE 8. Architecture of the ASTA System. The significant elements in the ASTA system include the ASDE-3 primary radar located on top of the control tower, the set of five to seven omnidirectional Mode-S receiver sites, the automatically controlled runway-entrance and takeoff-hold lights, and the ASTA processing facility located near the tower cab. The ASTA system extends Mode-S beacon surveillance to the airport surface by time-difference multilateration of squitter signals emitted by Mode-S transponders on the aircraft.

important safety benefits, which are the delivery of surface-traffic information to the cockpit and the use of direct cockpit alerts for time-critical safety messages.

The Delivery of Surface-Traffic Data to the Cockpit

The objectives of a high-capacity tower-to-cockpit digital data link are to reduce communications errors, improve pilot situational awareness, and assign pilots a greater share of responsibility for preventing movement errors. Because the best way to convey the surface situation for the flight crew is through a graphical display, this function should be combined with a surface moving map suitable for display in a *glass cockpit* or on a special display system. The term glass cockpit refers to advanced aircraft (such as the Boeing 757 and Airbus 320) that employ cathode-ray tube displays on their instrument panels in place of conventional electromechanical instruments.

A moving-map system could be part of an autonomous surface-navigation system that will reduce navigation errors. Figure 9 illustrates a possible method for implementing these capabilities. The top half of the diagram represents autonomous navigation and is based on a precision surface-navigation system such as differential GPS, with additional on-board equipment to store and display surface maps. Read-only memory modules in the on-board equipment will contain the stored maps, and these modules will be periodically updated and replaced. The bottom half of Figure 9 represents the development of surface-traffic data, including airport configu-

Table 5. Five Development Areas for Tower Automation

Surveillance	• Primary Radar (ASDE-3 or Equivalent) • Radar Processing Interface and Algorithms to Track Targets • ARTS-to-Radio-Beacon-System Interfaces to Monitor Approach Paths • Mode-S/ATCRBS Multilateration Surveillance
Communications	• Mode-S Digital Data Link • Data-Link Interfaces to Other FAA Communications Systems • Data-Link Applications • Cockpit Equipment
Safety	• Safety Algorithms • Automatic Runway-Status Lights • Surface-Movement Guidance and Control Lights • Airport-Status Interfaces • Operational Procedures
Traffic Management	• Traffic-Management Algorithms • Integration into TCCC • Integration with Other ATC Automation Systems (TATCA, AERA, and ETMS)
Human Factors	• Controller Interface • Real-Time Laboratory Experimental System

Table 6. Automation Products for the Control Tower

Phase	*Product*	*Safety Benefit*	*Capacity Benefit*
ASDE-3	• Surface Radar	Major	Moderate
AMASS	• Audible Alerts in Tower Cab	Major	None
	• ASDE Display Enhancements	Moderate	Moderate
ASTA-1	• Runway Status Lights	Major	None
	• Runway Status on ASDE Display	Moderate	Moderate
ASTA-2	• Data Tags on ASDE Display	Major	Major
	• Traffic Management Aids (Departure Flow Management)	None	Major
	• Taxi-Route Compliance Monitoring	Major	None
	• Airport Configuration Management Aid	None	Moderate
ASTA-3	• Surface Traffic Data in Cockpit	Major	None
	• Direct Cockpit Alerts	Major	None
	• Active Taxi-Route Guidance	Major	Moderate
	• Traffic Planning Coordination (with TATCA and Central Flow)	None	Major
	• Unloading Ground Voice Channel	None	Major
	• Data-Link Services	None	Major

ration information, and the delivery of that data to the cockpit via the Mode-S data link.

The ASTA Safety System

The process of building a comprehensive safety system for the airport surface must include an examination of existing equipment and procedures to determine how to integrate new capabilities. Two important safety-related systems will precede ASTA-1; these are the new ASDE-3 primary surface radar and the alerting system called AMASS, which was described earlier. The development of AMASS by Norden Systems is now under way, and a field test of a preproduction unit is scheduled at San Francisco International Airport beginning in 1992. If tests of the preproduction system are successfully completed, production AMASS systems will be implemented as add-ons to the ASDE-3 surface radars.

The safety products that will be implemented under the AMASS program are (1) audible alerts in the tower cab and (2) enhancements to the ASDE-3 (or equiva-

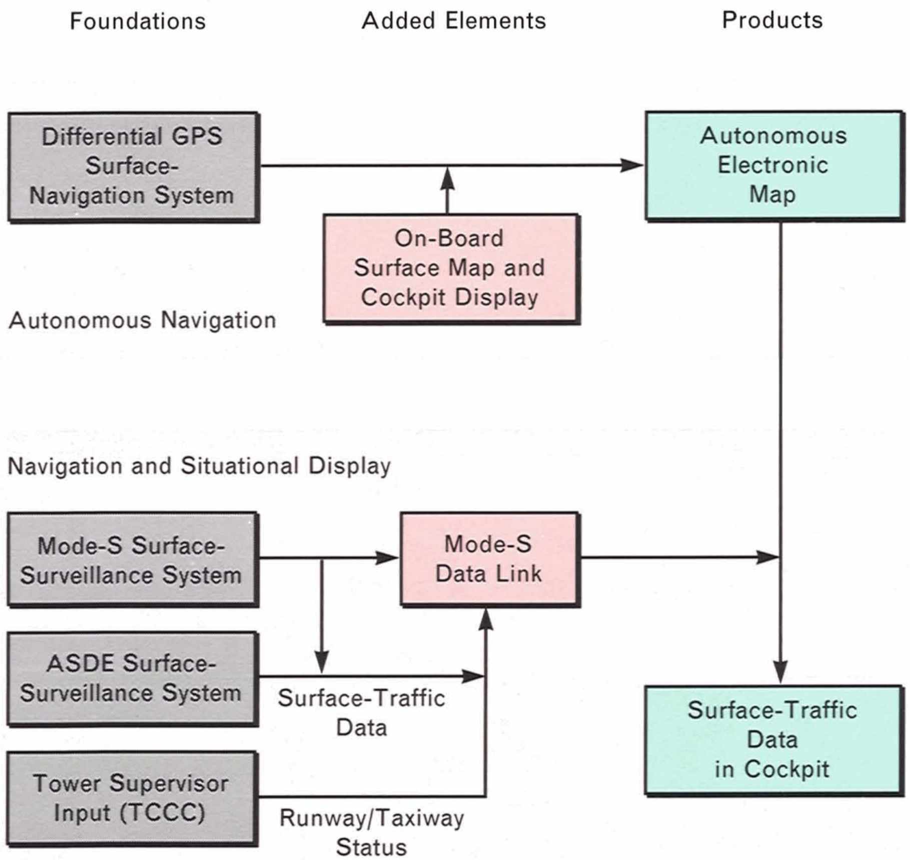


FIGURE 9. Cockpit maps and surface-traffic data. A major airport is a vast sea of concrete and lights, and pilots often have trouble finding their way around the surface. For this reason, an autonomous moving-map surface-navigation system for the cockpit is under development. The foundations include a precision surface-navigation system (such as a modified form of the satellite-based global positioning system), a stored surface map, and a cockpit display. Because the spacing between runways and parallel taxiways is typically a few hundred feet, the required navigational accuracy to support moving maps is on the order of 10 to 20 ft. The augmentation of a moving-map system to permit the delivery of surface-traffic data to the cockpit will require a tower-to-cockpit data link such as that provided by Mode S. Traffic data and runway or taxiway status will be obtained from the combination of multilateration, ASDE surveillance systems, and the tower supervisor's input through the Tower Control Computer Complex.

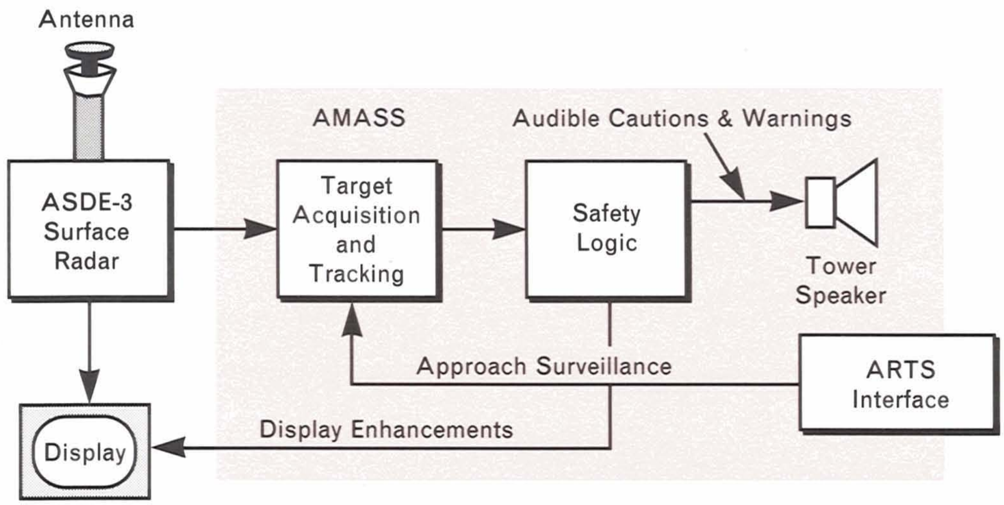


FIGURE 10. The Airport Movement Area Safety System (AMASS). AMASS is being implemented as an add-on to the ASDE-3 radars planned for 29 major domestic airports; it is based on a combination of electronic surveillance, safety logic, and an audible alerting system in the tower cab. AMASS obtains surveillance data of the airport surface by tapping the digital data stream in the ASDE-3 radar. It then processes the data to suppress clutter, and locates and tracks aircraft within the movement area. It obtains surveillance of the approach airspace through an interface to the ARTS computer located in the TRACON that serves the airport. When these combined data are analyzed by safety logic, situations that represent safety hazards are automatically detected and tower controllers receive both audible and visual alerts. The introduction of AMASS at ASDE-3 sites represents the first step in the FAA's program to implement automatic systems to improve airport safety.

lent) surface radar display. These capabilities are based on the processing of target data extracted from the ASDE-3 radar and an interface to the ARTS computer. Figure 10 shows a block diagram of the AMASS system. The block labeled ARTS Interface obtains surveillance data from the ARTS computer located in the TRACON, and the ARTS computer obtains surveillance data from a terminal-area airport surveillance radar such as an ASR-7 or ASR-9. These data, which cover the approach paths, permit the safety system to alert controllers when the runway ahead of a landing aircraft is not clear. This obstructed-runway scenario occurred in two of the last three major surface accidents (in Atlanta and Los Angeles), which highlights the importance of this coverage.

When a runway incursion occurs, or appears imminent, AMASS issues an audible alert and places indications on the display to aid the controller in a rapid analysis of the situation. AMASS also provides other display enhancements that are useful for routine operations, including an *approach bar* for each active runway. The approach bar is a short line segment representing the airspace between the runway threshold and the outer marker (approximately 5 nmi out). The approach bar can be continuously shown on the display or, at the controller's option, only when an alert has been issued. When the terminal radar detects a landing aircraft at or within the outer marker, a symbol representing the aircraft position is added at the corresponding point on the approach bar.

AMASS represents an important first step in improving safety at major domestic airports. Unfortunately, when AMASS sounds the alert, a runway incursion has already occurred (in most cases); this fact means that AMASS will not have a major impact on the number of operational errors and pilot deviations, which are the principal causes of incursions. In addition, the system will have limited effectiveness for time-critical incidents. For these incidents, the system must focus on the prevention of the movement error rather than remedial action after an error has already occurred.

Table 7. Requirements for Automatic Backup Systems

Category	*Requirements*
Human Factors	• No Increase in Workload • Independent of Controllers and Pilots • Low Nuisance-Alarm Rate[1] • Low False-Alarm Rate[2] • Provides a Second Pair of Eyes • Systems to Back up Both Controllers and Pilots
Technical Factors	• Best not to Require New Equipage on Aircraft • Low Missed-Detection Rate
Operational Factors	• Must not Interfere with Normal Operations • No Major Changes in Operational Procedures • Focus on Safety, not the Rules • No Adverse Impact on Capacity • Must not Usurp Controller's Authority

1. A nuisance alarm is an alarm that, although an accurate reporting of the situation, is unnecessary and thus not desirable.
2. A false alarm is an inaccurate reporting of the situation and thus highly undesirable.

Prevention—The Key to Safety

Inadequate situational awareness often contributes to runway incursions or accidents. For this reason, the ASTA safety system and the systems that precede it include elements that improve situational awareness for both controllers and pilots. A reliable, low-clutter ASDE-3 radar display with data tags will greatly improve the controller's ability to monitor the surface situation, especially during periods of low visibility. For the pilot, the elements that help prevent movement errors include the runway-status lights, the display of surface-traffic information in cockpits, active taxi-route guidance, and the use of direct cockpit alerts.

Automatic Backup Systems

The effort of developing an airport surface safety system has two directions. The first direction addresses the difficult task of improving human performance by providing better surveillance, communications, processing, and navigation tools for both controllers and pilots. The second direction addresses the implementation of a set of automatic backup systems that protect against human error. These automatic systems must, for the foreseeable future, operate in a human-centered environment where the prime responsibility and the majority of the activity remains in the hands of controllers and pilots.

Table 7 summarizes the requirements for any automatic backup system in an airport control-tower environment. Some of these constraints require that the automation must neither distract controllers nor interfere with normal operations. In addition, an automatic backup system must minimize any adverse impact on airport capacity. Finally, the regulatory and economic impact of new equipage on aircraft suggests that systems that either minimize or eliminate new equipage will fare best in the competition for support within the commercial aviation community.

Active Surface Lights

The International Civil Aviation Organization (ICAO) Surface Movement Guidance and Control (SMGCS) manual [6] states the following about runway incursions:

> The primary means of protection must be the provision of sufficient *visual information* to pilots and drivers that they are approaching an active runway in order to conform with the recognized procedures.

In other words, pilots and drivers must not only know they are approaching a runway, they must know which runway it is, the direction it runs, and if it is closed, inactive, or active. Common sense also suggests that they should know if entering the runway will be hazardous. For these reasons, the use of both static and dynamic surface lights is an integral part of the ASTA safety system.

We make the distinction between existing light systems, many of which are only used at night or during low visibility, and the full-time dynamic lights operated either manually by controllers or automatically by the safety system. Figure 11 illustrates some of the existing runway and taxiway light systems. Not shown in the figure are additional existing lights for the touchdown zone, the identification of the approach end of the runway, the glide slope, and the approach path.

In Europe, manually controlled surface guidance lights and other special low-visibility procedures are used at several of the major airports, such as London (Heathrow), Paris (Charles de Gaulle), Amsterdam (Schiphol), and Frankfurt. Many of these systems were implemented because of prevailing fog conditions and are operated manually by individuals designated as light operators. In effect, the manually controlled lights assist pilots in following their assigned taxi route and thus prevent aircraft from becoming lost while taxiing between the ramp area and the runways.

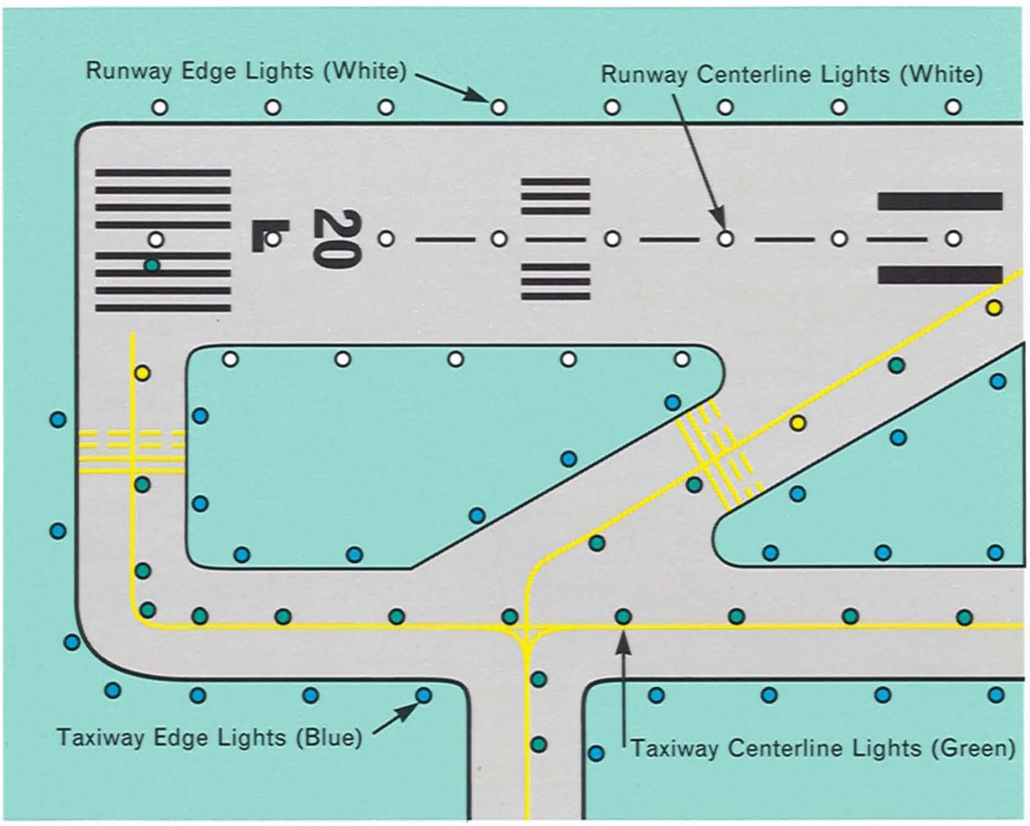


FIGURE 11. Runway and taxiway lights. On a clear night, the lights on an airport surface can confuse even the most experienced pilot. Standard surface lights include the blue taxiway edge lights, the white runway edge and centerline lights, and the green taxiway centerline lights. Both runway and taxiway centerline lights are located in the pavement and are bidirectional while the edge lights are on short posts and are omnidirectional. The taxiway centerline lights that indicate a high-speed exit from a runway are alternately amber (yellow) and green, until the taxiway holding position where they are all green. Other surface lights not illustrated in the figure include lighted runway and taxiway identification signs, runway-end identifier lights, and lights showing the glide slope.

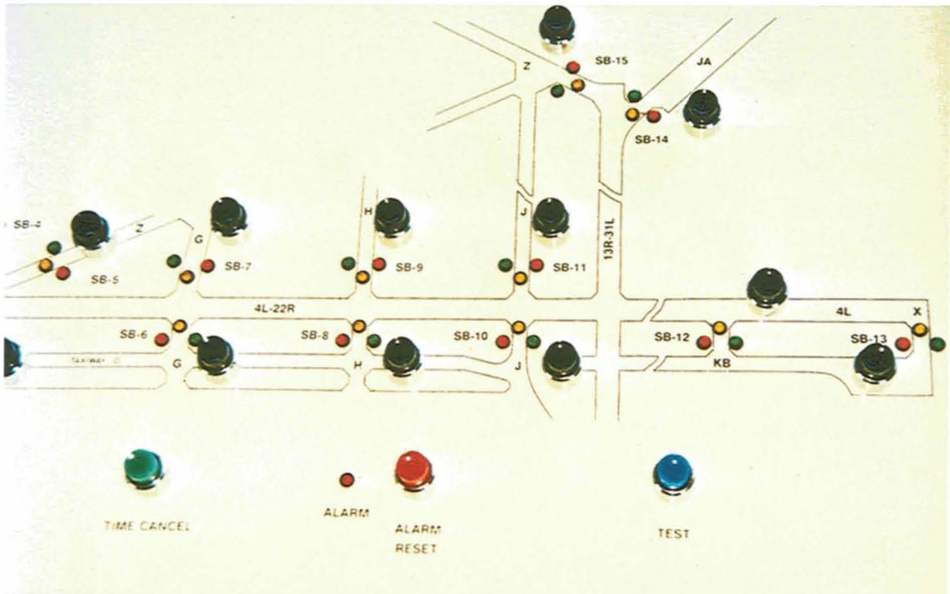


FIGURE 12. The control panel for an experimental system of manually controlled runway-entrance lights at John F. Kennedy International Airport. A local controller issues a verbal clearance for an aircraft to enter or cross an active runway and presses the appropriate activation button on the panel. The entrance lights, which are normally red, then turn to green for a fixed period of approximately 20 sec. One problem has been that the lights can revert to red before the aircraft has passed, and thus pilots stop and query the controller whether the clearance has been canceled.

Boston and New York Experiments

Although runways and taxiways in the U.S. are marked by a combination of signs, painted markings, and lights, there is essentially no use of lights in a dynamic mode to indicate runway status or clearances. Two exceptions are experimental systems at John F. Kennedy Airport in New York and at Logan Airport in Boston. The system at Kennedy Airport incorporates red/green *stopbars* at all entrances to one of the four major runways (4L/22R) plus two entrances at one end of another runway (31L). The local controller, or a second controller, turns these lights, which are normally red, to green at a desired intersection by using a small control panel (see Figure 12). This system, which increases workload and requires the controller, when not assisted by a second person, to look down to select the proper button, can introduce controller error. For example, if the controller fails to notice an aircraft on final approach and clears another aircraft to position and hold, the operation of the clearance light will reinforce the error (the stopbar lights turning from red to green provide the pilot with a visual confirmation of the verbal clearance issued by the controller, even if that clearance results in an unsafe situation). With the implementation of an automatic override feature in the ASTA safety system, this problem will be eliminated.

The Logan Airport light system, which could be called semidynamic, is designed to permit simultaneous operations on two intersecting runways. Aircraft landing to the south on the north/south runway 22L are instructed to come to a full stop (to *hold short*) before reaching the intersection of 22L with the east/west runway identified as 9/27. To assist pilots in identifying the hold-short point, the system uses a set of five in-pavement white lights. These lights turn on and off once per second to provide a unique visual indication of the hold position. When hold-short operations on runway 22L are in process, the controller flips a switch to activate the lights. If a landing aircraft requires the full length of the runway, it is cleared verbally and the pilot is authorized to ignore the lights. To avoid possible pilot confusion, the lights can also be turned off manually for the duration of each full-length landing operation. Even though the lights provide an important safety function, however, they still fail to protect against controller error.

ASTA's Runway-Status Lights

The ASTA program calls for two types of dynamic surface lights, namely, runway-entrance lights and takeoff-hold lights. These lights provide pilots and vehicle operators with the same information on runway status that any careful pilot can obtain by direct visual observation when visibility and light conditions permit (e.g., "Look both ways before crossing the street!").

Figure 13 illustrates the operation of the ASTA runway-entrance lights in conjunction with the ICAO taxi hold-position lights (commonly called *wig-wag* lights because they alternate on and off). When the area manager determines that a particular runway is to be used for takeoffs or landings, he or she notifies the tower supervisor, who in turn flips a switch to activate the wig-wag lights at all taxiway entrances to the runway. These lights remain active until a decision is made later to cease operations on that runway. The functions of the wig-wag lights are to identify the runway as active and define the holding position for taxiing aircraft instructed to hold short of the runway.

The wig-wag lights are controlled manually, but the ASTA runway-entrance lights are entirely automatic. When the surveillance data indicate that an aircraft whose trajectory is aligned with the runway is landing, taking off, or otherwise approaching the intersection with a particular taxiway, the ASTA runway-entrance lights at that intersection are automatically turned on (red). This transition is based on a complex logic that concerns safety rather than specific separation standards or other rule-based criteria. The determination to activate a particular entrance light is based on the concept of a *hot zone* (an area that is not safe to enter) that extends in

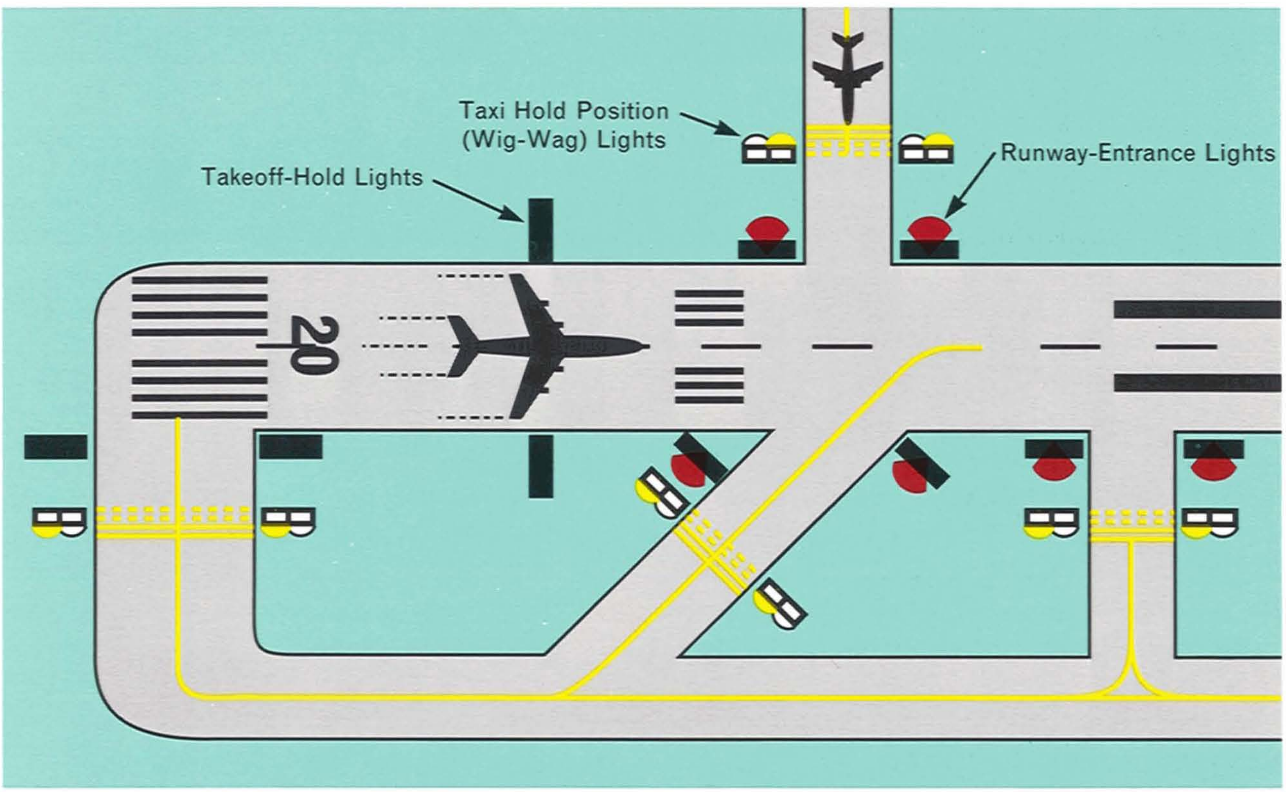


FIGURE 13. Operation of ASTA runway-entrance lights. The ASTA runway-entrance lights are operated automatically by safety logic that monitors aircraft position, velocity, and acceleration. When the safety logic determines that a particular intersection is unsafe to enter, the runway-entrance lights turn from off to red. When the aircraft that created the condition passes the intersection, the lights automatically revert to off. The lights are independent of controller intent so they will contradict rather than reinforce human error. This independence also insures that the lights do not add to controller workload.

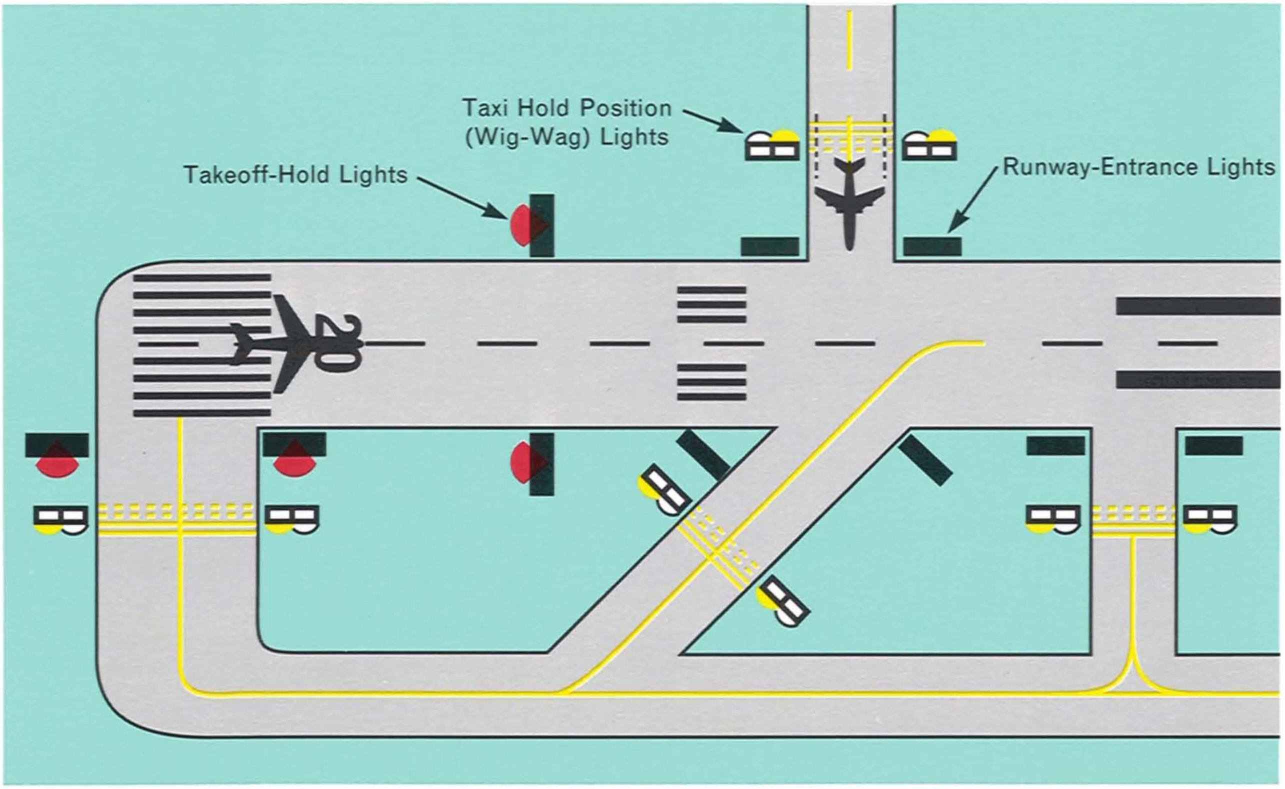


FIGURE 14. Operation of ASTA takeoff-hold lights. The ASTA takeoff-hold lights, like the runway-entrance lights illustrated in Figure 13, are operated automatically. When an aircraft is on the runway in one of the positions defined as a starting point for takeoff, and the full runway ahead is not safe for takeoff, the takeoff-hold lights automatically turn from off to red. The unsafe condition is another aircraft or vehicle either on the runway or projected to enter the runway at a time that would pose a collision hazard if the takeoff were to begin. When the safety system detects that the potential hazard has passed, the lights automatically revert to off. Because this system is independent of controller or pilot intent, it will contradict most human errors.

front of an aircraft.

In general, the extent of the leading portion of the hot zone is based on a time horizon that sweeps ahead of the aircraft. The specific time parameter depends on whether the airplane is approaching, landing, taxiing, or taking off. To allow for imperfect surveillance, the trailing portion of the hot zone is usually a fixed length correlated with the size of the target aircraft as seen on radar. As the aircraft passes each intersection, the entrance lights revert to off, which avoids possible interference with normal surface-traffic movements.

The automatic operation of the ASTA runway-entrance lights does not depend on the status (closed, inactive, or active) of the runway. For example, an aircraft that begins a landing approach to an inactive or closed runway (because of pilot error) would cause the entrance lights to turn from off to red (hot); it would also result in audible alerts in the tower cab and a significant amount of paperwork for the pilot to fill out after landing.

In many ways the runway-entrance lights mimic the warning lights at a railroad grade crossing, but there is an important distinction. Railway lights are activated when the train reaches a fixed distance from the crossing, independent of the train's speed. Thus a stationary train can activate lights when no safety hazard exists. For ASTA, the use of a time horizon rather than a simple distance parameter eliminates this problem.

The second type of ASTA light is the takeoff-hold light as shown in Figure 14. A red hold light in front of the aircraft in position for takeoff indicates that the runway ahead is either not safe, or shortly will be not safe.

The ASTA entrance lights and takeoff-hold lights turn red based solely on the motion of the targets (aircraft and vehicles). They do not depend on controller or pilot intent. This important safety consideration avoids an increase in controller workload and provides an automatic backup to guard against human error. Because the conditions that cause the lights to turn red are such that no controller would want an aircraft or vehicle to cross the red lights, they will not interfere with normal traffic. A further consideration is that the control algorithms for the lights are designed to achieve safe surface operations; they are not intended to enforce separation standards or other rules.

Requirements for Runway-Status Lights

We designed the operation of the runway-status lights as described above to satisfy six important considerations: (1) the runway-status lights must not add to controller workload, (2) the lights must neither interfere with controller clearances nor impede the normal flow of traffic, (3) the presence of the lights must be essentially transparent to the controller (with the exception of an occasional override), (4) the lights (and the rest of the automation system) must not increase *heads-down* time, (5) the lights must never be visible to an aircraft during the high-speed

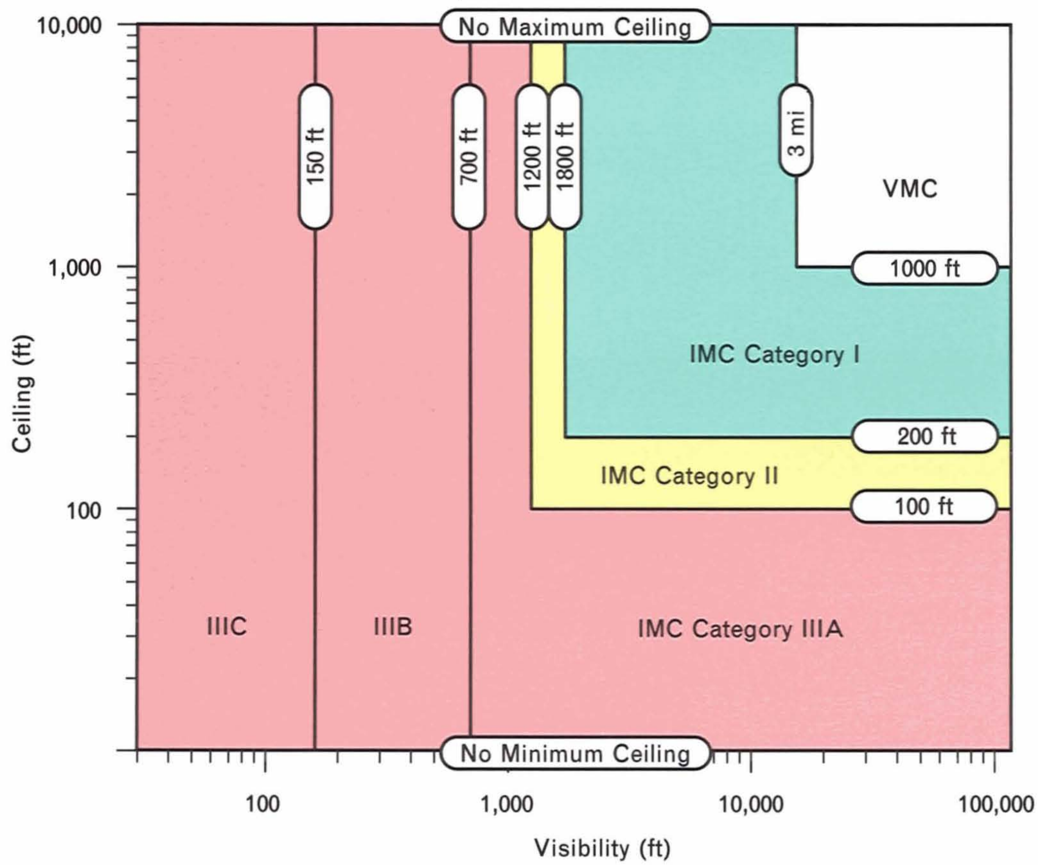


FIGURE 15. Ceiling and visibility conditions under which visual and instrument rules apply. When visual meteorological conditions (VMC) exist, aircraft can be vectored into position and cleared for a visual approach. When instrument meteorological conditions (IMC) prevail, aircraft at major airports normally make precision instrument approaches that fall into one of three broad categories (I, II, and III). All precision approaches under these categories employ a combination of ground and cockpit equipment that provides both lateral and vertical guidance. Approaches under Categories II and III require aircraft with special equipment and flight crews with special training. Category IIIC landings are essentially no-visibility landings and are conducted hands off with the on-board autopilot controlling the aircraft through touchdown and roll out. Not shown in the figure are the limits for nonprecision approaches that provide lateral but not vertical guidance.

portion of takeoff or landing, and (6) the safety algorithms must allow for unique local procedures. The theme of these considerations is twofold; the lights must serve as protection against human error while not reducing airport capacity.

ICAO Surface Movement Guidance and Control System Lights

The use of dynamically controlled surface lights during low-visibility conditions at many foreign airports has already been mentioned. At most of these locations, the surface lights conform to standards developed by ICAO. At present, an ICAO-SMGCS working group has published a draft report that proposes a system of manual and automatic lights to guide and control aircraft during low-visibility conditions. In addition, the FAA is preparing an Advisory Circular covering requirements for airports that want to conduct flight operations when the surface visibility along the runway is 600 ft or less.

To discuss the application of ICAO-SMGCS light systems to low-visibility operations, we must first identify the ceiling and visibility limits that define the various landing-condition regimes. Figure 15 outlines the ceiling and visibility limits that define VMC and the three basic categories of IMC for which some form of instrument-landing system and corresponding aircraft equipment is required. (The figure does not show the division of IMC Category I into those conditions requiring precision and nonprecision approach systems.) All IMC Category II and Category III conditions call for additional aircraft equipment as well as special flight crew training.

Not all major domestic airports are equipped for Category II or III landings; for example, only four of the 23 instrument approaches defined for O'Hare International Airport's seven runways are either Category II or III. The limiting values shown in the figure are typical; specific limits for a particular approach can be higher depending on the surrounding terrain, the accuracy of the instrument landing system as installed, and the approach speed of the aircraft. In addition, airlines and other operators often impose limits that are more restrictive than those specified by the FAA. Most instrument approaches in the U.S. occur under conditions better than the limits for Category I.

Excluding nonprecision approaches (which have a ceiling typically greater than 600 to 800 ft and visibility greater than 2 mi), all IMC Category I, II, and III approaches require some form of instrument-landing system. Table 8 lists the *decision height*, or ceiling, and runway-visual-range visibility criteria for each instrument-landing-system category.

The proposed ICAO-SMGCS surface lights can be divided into semiautomatic taxiway guidance lights and manually controlled lights that guard entrances to runways. The taxiway guidance lights serve an important function, but they are not impacted by the ASTA concepts and are not described in detail here. Figure 16 illustrates the placement and function of the SMGCS runway-entrance lights. These lights include taxi hold-position lights (wig-wag lights) located in pairs on each side of the taxiway and a line of in-pavement stopbar lights across the taxiway. The wig-wag lights are located at the Category I hold position while the stopbar lights are farther back from the runway at the Category II and III hold position. In this country these positions are identified officially as the *taxi hold position* and the *instrument-landing-system critical hold position.* The stopbar lights would be used only when ceiling and visibility are sufficiently low to require operations under Category II or Category III rules. Figure 16 also indicates the standard blue taxiway edge lights, taxiway centerline lights (which are either off or green), and the proposed ASTA runway-entrance lights.

When a runway is designated as active, a tower controller will flip a switch to activate amber (yellow) wig-wag lights at the Category I taxi holding positions of all entrances to the runway. If conditions are at or above the Category I limits, pilots instructed to hold short of an active runway will stop at the Category I hold position as designated by the on-pavement markings and the wig-wag lights. Should visibility drop below the value at which FAA standards require positive control at entrances to Category II and III runways (nominally 600-ft runway visual range), a tower controller will activate the red stopbar lights at the Category II and III taxi holding positions, as shown in Figure 16. Then, as an aircraft is given verbal clearance to taxi onto the runway, the controller will press a button to extinguish the red stopbar lights and illuminate the green centerline lights leading from that hold position out onto the runway. This action provides both visual confirmation of the verbal clearance and guidance to the takeoff position on the runway.

Table 8. Instrument-Landing Condition Criteria

Instrument-Landing System Category	*Lowest Decision Height*	*Lowest Visibility Minimum in Runway Visual Range (RVR)*
I	200 ft	1800 ft
II	100 ft[1]	1200 ft[2]
IIIA	None	700 ft
IIIB	None	150 ft[3]
IIIC	None	None

1. The lowest decision height is 150 ft until the flight crew meets certain experience requirements.
2. An RVR of 1600 ft is the limit until the flight crew meets certain experience requirements.
3. An RVR of 600 ft is currently the lowest approved Category IIIB minimum for any U.S. instrument-landing-system runway.

Because stopbars at all other Category II and III hold positions remain red, unauthorized entry by other aircraft is prevented.

For most current systems, the lights automatically revert to their original state, based either on signals from in-pavement sensors or a predefined elapsed time. If ceiling and visibility correspond to the Category I limits or better, the stopbar shown in the figure is off at all times in the ICAO-SMGCS concept. The ASTA runway-entrance lights, which are independent of the ICAO lights, continue under fully automatic control in all weather conditions. These lights advise pilots, irrespective of clearances issued from the tower, whether the runway is safe to enter. In addition, in low-visibility conditions the ASTA safety system can override a controller clearance to enter the runway by forcing the stopbar lights to remain red whenever the entrance of an aircraft or vehicle would create an unsafe condition.

Integration of ASTA Runway-Status and ICAO Lights

Because the ICAO-approved lighting systems are internationally standardized, the ASTA runway-entrance lights must be fully compatible with the SMGCS proposal. Figure 16 illustrates how this compatibility is created by the simple addition of ASTA runway-entrance lights located on either side of the taxiway at the edge of the runway. Because these entrance lights are operated automatically, based on surveillance and not controller or pilot intent, they are essentially independent of the ICAO stopbar and other lights. If a controller issues a clearance to an aircraft to enter the runway while another aircraft is approaching that intersection at high speed, the ASTA runway-entrance lights would turn on (red), thereby providing the pilot with a direct visual indication that entry is unsafe at that time. Presumably the same logic that activates the runway-entrance lights would, in an integrated system, automatically override any attempt by the controller to deactivate (turn from red to off) the ICAO stopbar. This automatic operation provides an important barrier to prevent runway incursions or accidents caused by controller error or pilot error.

Additional ASTA Safety System Elements

The ASTA-1 safety system is a combination of the ASTA runway status lights plus the integration with AMASS alerting functions. To this system ASTA-2 will add the implementation of data tags on the ASDE display, which is an important safety feature, and an initial taxi-route compliance monitoring function. In simplified terms, the ASTA-2 system will monitor routes taken by individual aircraft while comparing that route with the nominal path based on the present runway configuration in use, the initial departure fix, and the type of aircraft. For example, a Boeing 747 whose flight-route clearance indi-

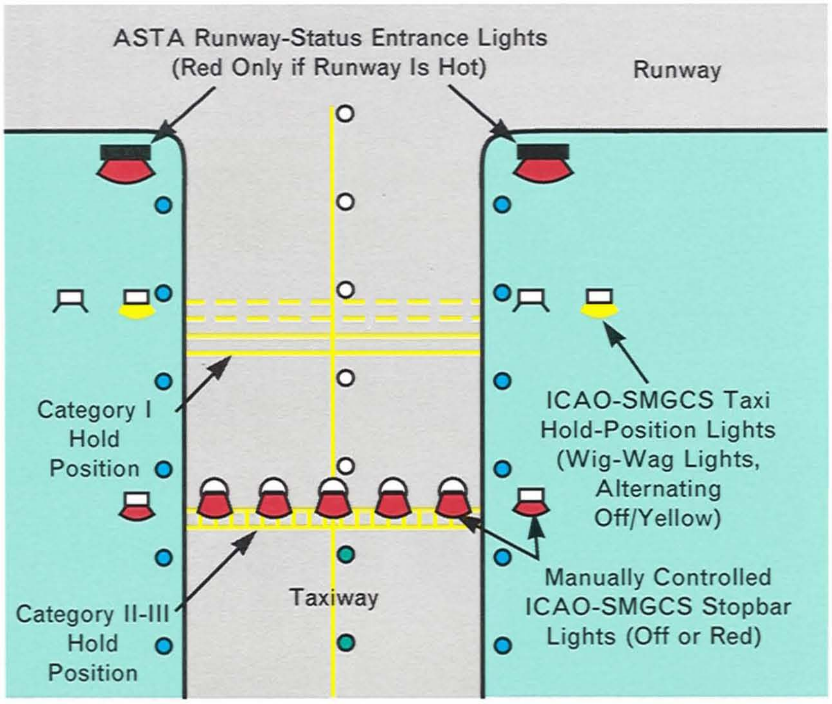


FIGURE 16. Integration of ICAO and ASTA entrance lights. This diagram illustrates the integration of the low-visibility ICAO runway-entrance stopbar at the Category II-III hold position, the ICAO Category I taxi hold position wig-wag lights, and the ASTA runway-entrance lights. The ASTA lights operate automatically in all weather conditions, while the ICAO stopbar at the Category II-III hold position is manually controlled and operated only when conditions are below Category I minimums. The ICAO wig-wag lights are continuously in use while the runway is designated as active.

cates an overseas destination would be expected to depart on the longest available runway. In the event that the safety system detects a movement inconsistent with a taxi route to the appropriate runway, the system could issue a caution to the ground controller.

The ASTA-3 system completes the safety functionality of ASTA by incorporating the Mode-S digital data link. This link permits the delivery of direct alerts to the cockpit, as well as surface-traffic data (to prevent navigational errors and promote situational awareness) and point-by-point taxi-route guidance instructions.

Traffic Management in ASTA

The highly integrated system of air traffic control will be significantly augmented over the next two decades by the implementation of the AAS, along with the four new traffic automation systems represented by TATCA, AERA, ASTA, and ETMS. Figure 17 illustrates the relationship between these systems. The ASTA system, with its safety and capacity components, resides in the control tower, while the TATCA and AERA systems are found in the TRACON and en-route center, respectively. These three domains represent the overall tactical control of air traffic in the United States.

On a higher level, the Central Flow control functions and the Traffic-Management Units in each en-route center and TRACON facility provide strategic direction in responding to adverse weather, equipment difficulties, and overloading. The ETMS is being developed to improve Central Flow and distribute access to its data to all en-route centers.

The focus of the ASTA program to date has been on the development of concepts for a comprehensive safety system for the airport surface. As a consequence, the traffic-management functionality in ASTA has only been identified in general terms. We know that the main traffic-management elements will include a traffic planner, functionality to coordinate the plan with other traffic automation systems, and automation aids designed to interface the plan with the controller.

The ASTA Traffic Plan

It sounds like an oversimplification to state that airplanes tend to gather at airports. This simple fact, however, plays a dominant role in the management of air traffic. For example, the main task of approach controllers in the TRACON is to sequence and merge aircraft that arrive from several directions into one or more properly spaced linear streams aligned with runways. In a similar manner, ground and local controllers in the control tower must accomplish essentially the same functions in the management of taxiing and departing traffic before turning control of each flight to the departure controllers in the TRACON. At the heart of these tasks is the development of a dynamic plan for the conduct of the traffic. This plan must include details such as sequence, in-trail spacing with allowance for wake-vortex separation, aircraft performance, speed restrictions, timing, local weather conditions, noise abatement restrictions, and other special factors that can be temporarily imposed due to equipment outages or other conditions. In practice, the controller develops a mental picture of the traffic and bases a plan on this picture, combined with guidance from the traffic-management function, experience, training, instinct, and what we might call the rules.

Departure Sequencing in ASTA

The starting point for traffic-management functionality in the ASTA system is departure sequencing. ASTA-2 will include the initial algorithms for the selection of a proposed departure sequence for consideration by the tower controllers. This sequence will be based in part on the initial departure fix as specified in the flight-route clearances, commonly called *flight plans*, that are obtained by ASTA from an interface to the TCCC functionality. Additional factors include the aircraft weight

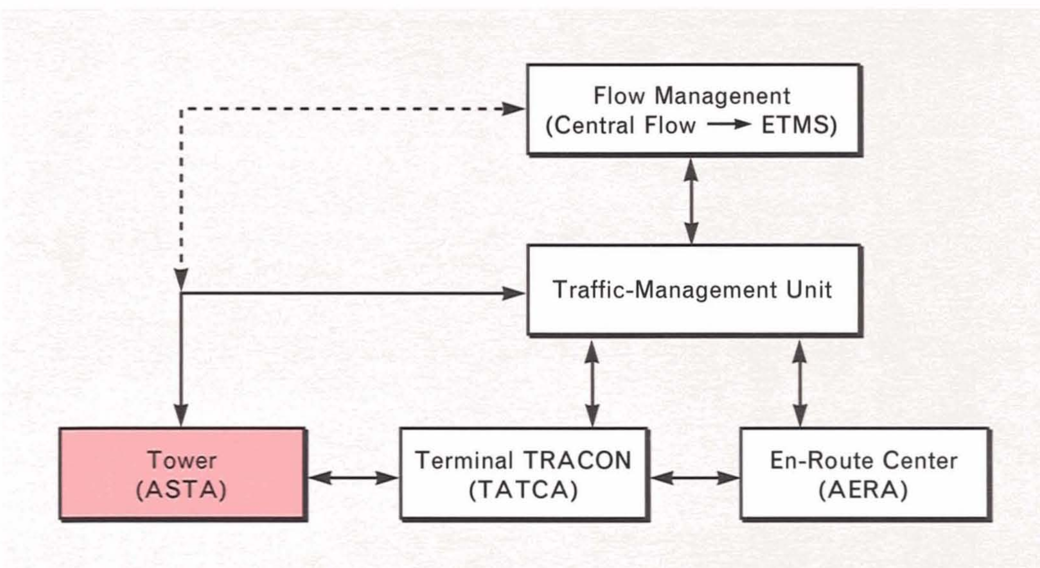


FIGURE 17. Integration of traffic automation systems. Automation aids are designed to assist controllers in all three types of ATC facilities in which the tactical control of air traffic is exercised. From ASTA on the airport surface and immediately surrounding airspace through TATCA in the approach and departure airspace to AERA in the en-route environment, the systems must provide for the automatic coordination under controller supervision of aircraft sequencing, spacing, and handoffs. Strategic control of domestic air traffic is exercised by a Central Flow control function in cooperation with traffic-management units in en-route centers. The Enhanced Traffic-Management System (ETMS) is being developed to provide Central Flow and traffic-management unit personnel with advanced automation tools.

class and performance, the origination point on the airport surface (the gate), and the need to avoid overloading departure controllers. For example, by sequencing a small aircraft such as a Lear Jet in front of, rather than behind, a heavy jet such as a Boeing 747, the required in-trail spacing to meet wake-vortex restrictions is reduced by several miles. Similarly, many advantages can be found by grouping aircraft into weight classes and alternating departure fixes. These factors must be accommodated by the ASTA traffic planner. In effect, we could state that a goal of the ASTA system is to provide tools to permit the least experienced controller to manage traffic as effectively as the most experienced controller.

ASTA Automation Aids and the Computer-Human Interface

Given that the role of automation is to assist the human controller, it is essential the the computer-human interface be the focus of a major developmental effort. At the heart of this interface is the set of software subsystems, called *automation aids*, that provide the functional interface to the traffic plan. The actual device used for the interface, such as a keyboard, trackball, mouse, touch screen, or voice-recognition system (a leading candidate), will play a major part in determining the effectiveness of the system. For example, if a controller chooses to alter the traffic sequence as proposed in the plan, he or she must input the change and receive confirmation that the plan has been altered. Clearly, the issues of heads-down time and the distraction factor for a tower controller will play a significant role in the development of the ASTA computer-human interface elements. Although the outcome is difficult to predict, the task is expected to be both difficult and challenging.

Coordination of Traffic Plans

An important ingredient in traffic automation is the provision for automatic coordination between controllers within the same facility as well as between facilities. Coordination within a tower cab under ASTA will be achieved in part by the use of a single dynamic traffic plan for the airport. Coordination with other air traffic control domains such as the TRACON, which handles approach and departure traffic, will be achieved by an ongoing sequence of electronic negotiations between the ASTA and TATCA systems. These negotiations will be based on a predefined set of optimization algorithms designed to maintain safety and reduce delays while allowing for spacing and other requirements governing the airspace surrounding the airport.

Modified FAA Ground-Delay Program

Let us examine an example of a coordination process involving ASTA. When Central Flow implements a ground-delay program, the intention is to control the arrival rate of aircraft to prevent overloading at a particular destination airport, sector, or fix. With the full implementation of the four traffic automation systems, this delay program can be accomplished by assigning arrival time slots (rather than the present method of assigning departure slots) for aircraft at a number of distant airports. Once the arrival slots are assigned, the three automation systems will then begin determining expected route times by considering winds aloft, sector loading, and aircraft performance. The process will work backward from the destination by, in turn, AERA, TATCA, and finally ASTA. Each system determines a desired handoff time from the preceding system at the relevant boundary fix and then passes that time in the form of an electronic coordination request message.

When ASTA at a particular airport receives a coordination request from the TATCA system at the TRACON, it proceeds to calculate the optimum pushback time so that the aircraft after taxiing and takeoff will meet the requested handoff time at the appropriate departure fix. This pushback time will depend on runway configuration, weather, and traffic density at that particular airport. ASTA will then attempt to fit these times into the traffic plan. If some adjustments are required to avoid unnecessary delays for other flights, ASTA may automatically transmit a change request for a revised handoff time to TATCA, which then can either elect to accommodate that request or pass a further change request on the AERA. The tools that each system has to work with in attempting to achieve convergence include vectoring, speed changes, and altitude changes. Once a final set of handoff times are agreed upon and approved by the relevant controllers, the three automation systems will then each monitor the flight's progress through its domain and determine small mid-course speed changes to fine-tune the process as the flight proceeds.

Conclusions

The ASTA safety and traffic-management system addresses the priorities for the airport surface as set forth by the Congress, the National Transportation Safety Board, and the Air Traffic Requirements Service of the FAA. It improves controller and pilot performance through better surveillance and navigation, and it implements automatic backup systems to guard against human error. In addition, it provides a dynamic traffic plan and supporting automation aids to assist tower controllers in managing traffic, including advance planning and coordination with other traffic-management domains.

These capabilities are produced by electronic surveillance of the movement area and approach airspace, a system of automatic runway status lights integrated with ICAO low-visibility lighting, safety and traffic-management algorithms integrated into the TCCC, digital data-link communications between tower and cockpit, and interfaces to other ATC automation systems. With adequate support, these capabilities could be in operation late in this decade at between 50 to 100 domestic airports.

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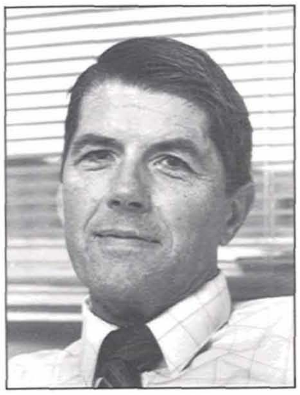

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