AIR TRAFFIC CONTROL

The United States air traffic management (ATM) system provides services to enable safe, orderly, and efficient aircraft operations within the airspace over the continental United States and over large portions of the Pacific and Atlantic oceans and the Gulf of Mexico. It consists of two components, namely, air traffic control (ATC) and traffic flow management (TFM). The ATC function ensures that the aircraft within the airspace are separated at all times, while the TFM function organizes the aircraft into a flow pattern to ensure their safe and efficient movement. The TFM function also includes flow control such as scheduling arrivals to and departures from the airports, imposing airborne holding due to airport capacity restrictions, and rerouting aircraft due to unavailable airspace.

In order to accomplish the ATC and TFM functions, the ATM system uses the airway route structure, facilities, equipment, procedures, and personnel. The federal airway structure consists of lower-altitude victor airways and higher altitude jet routes (1). The low-altitude airways extend from 1200 ft (365.8 m) above ground level (AGL) up to, but not including, 18,000 ft (5486.4 m) above mean sea level (MSL). The jet routes begin at 18,000 ft (5486.4 m) and extend up to 45,000 ft (13,716 m) above MSL. A network of navigational aids mark the centerline of these airways, making it possible to fly on an airway by navigating from one navigational aid to the other. The airways are eight nautical miles wide. Figure 1 shows the location of the jet routes and navigation aids that are within the airspace controlled by the Oakland and Los Angeles Air Route Traffic Control Centers. The jet routes are designated by the letter J, such as J501. Navigation facilities are indicated by a three-letter designation such as PYE.

Four types of facilities are used for managing traffic. They are the flight service stations (FSSs), air traffic control towers (ATCTs), terminal radar approach controls (TRACONs), and air route traffic control centers (ARTCCs) (1). These facilities

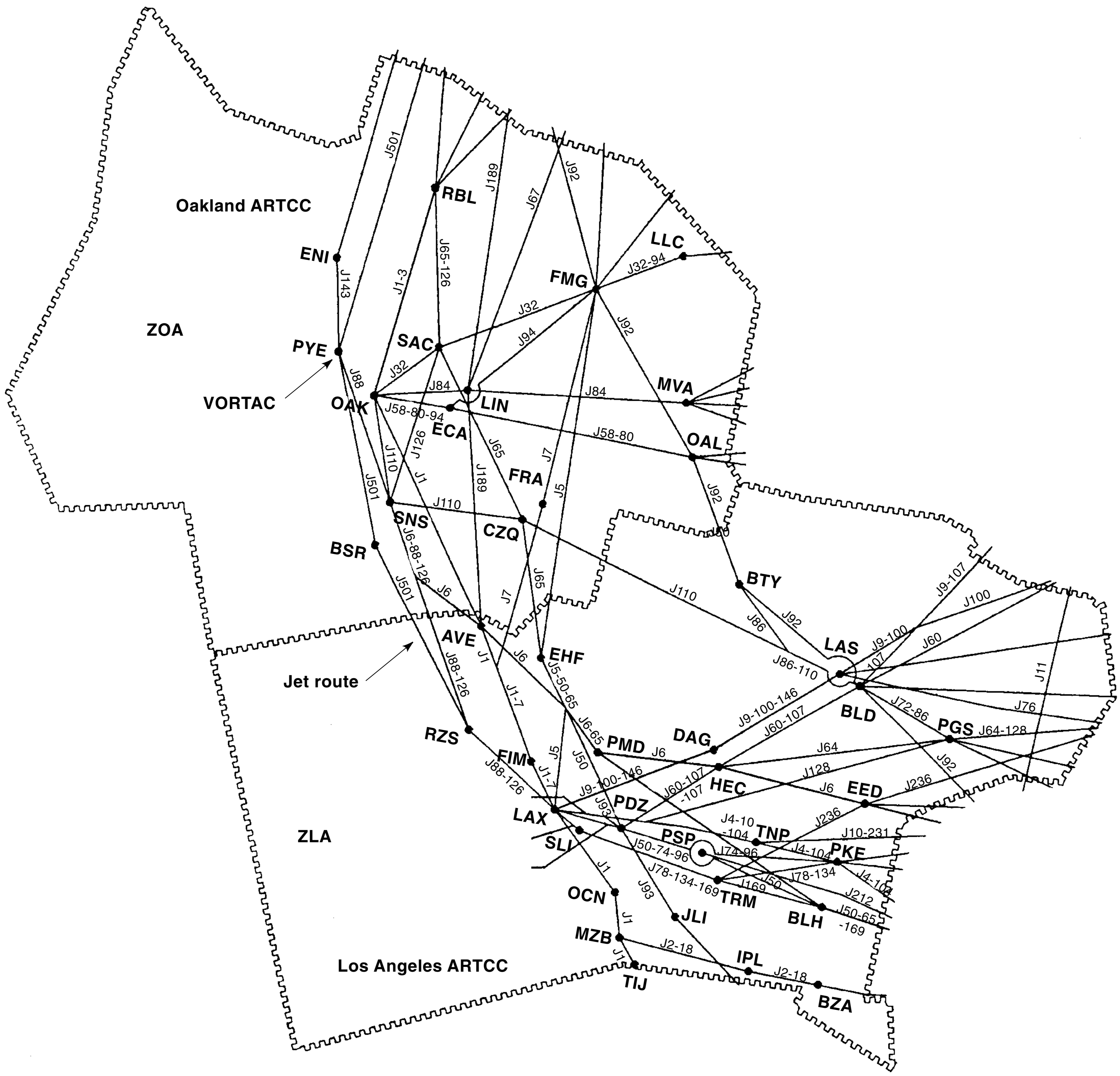

Figure 1. Oakland and Los Angeles Air Route Traffic Control Center airspace.

provide service during different phases of flight. The flight service stations provide preflight and inflight weather briefings to the pilots. They also request the flight plan information which consists of the departure and arrival airports, airspeed, cruise altitude, and the route of flight, which they pass on to the ARTCCs. Flight plan filing is mandatory for flight operations under instrument flight rules. It is not required for flight operations under visual flight rules but it is highly recommended. The ATCTs interact with the pilots while the aircraft are on the ground or shortly into the flight. During a part of the climb, the TRACONs are responsible. TRACON airspace, known as terminal control area (TCA), is in the shape of an upside-down wedding cake. At higher altitudes, the ARTCCs take on the responsibility for providing the ATM services to the aircraft. The process is reversed as the aircraft nears the destination airport.

The main types of equipment used in ATM are the radars, displays, computers, and communications equipment. Radars provide information regarding the positions of the aircraft within the airspace. This information is processed in conjunction with the flight plans to predict future locations of the aircraft. The display of this information is used by the air traffic controllers in the facilities to determine if the established rules and procedures would be violated in the near future. To prevent violations, the air traffic controllers issue clearances to the pilot to modify the flight path of the aircraft such as to speed up, slow down, climb, descend, and change heading. The procedures used by the air traffic controllers and pilots include rules and methods for operations within the particular airspace. For example, the rules define the minimum separation distance between any two aircraft, the authority of an individual facility over the airspace segment, the transfer of responsibility from one facility to the other, and the phraseology for verbal communications. For pilots, these rules specify their responsibility and authority, flight and navigation procedures, reporting requirements, and compliance with ATM instructions. The communications equipment enable both voice and computer-to-computer communications. Voice communication is used between pilots and the ATM facilities and also between ATM facilities. Information transfer from one facility computer to the next is done using the communications equipment.

HISTORICAL DEVELOPMENT OF THE ATM SYSTEM

The present-day ATM system in the United States has evolved in response to the needs of the several different groups of users and providers of the ATM services (2). These groups include air carrier, air taxi, military, general aviation, business aviation, pilots association, and air traffic controllers association. The ATM system has changed with technological advancements in the areas of communication, navigation, surveillance, computer hardware, and computer software. Detailed historical accounts of ATM development are available in Refs. 1 and 3. In the history of ATM development, five periods are easily identifiable. Early aviation developments took place during the period from 1903 to 1925. This period saw the development of aircraft construction methods, use of radio as a navigation aid, nighttime navigation using ground lighting, and the development of airmail service. The important legislative action that marks this period is the Airmail Act of 1925, which enabled the Postmaster General to contract with private individuals and corporations for transporting mail. An important consequence of this Act was that companies like Boeing, Douglas, and Pratt and Whitney got into the business of supplying aircraft and engines to the budding airmail industry. With the increase in air traffic activity, a need for regulation was felt to unify the industry through common sets of rules and procedures. An advisory board made its recommendation in the Morrow Report which led to the signing of the Air Commerce Act into law in 1926. This Act marks the beginning of the second period of ATM development.

The period between 1926 and 1934 saw Charles Lindbergh's flight across the Atlantic, installation of ground-to-air radio in aircraft, development of ground-based radio navigation aids, airline aircraft equipped with two-way radio telephone, radio-equipped air traffic control tower, and the development of a new generation of faster higher-flying transport aircraft capable of being flown solely with reference to cockpit instrumentation. The third phase of the ATM development is marked by the creation of the Bureau of Air Commerce in 1934.

During the third phase that lasted until 1955, numerous changes took place that shaped the ATM system to its present form. The principal airlines established interline agreements in 1935 to coordinate traffic into the Newark, Chicago, and Cleveland airports. The center established at Newark became the first airway traffic control unit (ATCU) in the world. In 1938, the US Congress created the Civil Aeronautics Authority which in 1940 was reorganized as the Civil Aeronautics Administration (CAA). This period saw the development of visual flight rules (VFR) and instrument flight rules (IFR). The civil airways system, controlled airports, airway traffic control areas, even and odd altitude levels, and radio fixes for mandatory position reporting by IFR aircraft were established during this phase. By 1942, 23 ARTCCs (former ATCUs) provided coverage of the complete continental airways system. During the World War II years between 1941 and 1945, the CAA set up approach control facilities at the busiest airports to separate arriving and departing aircraft out to 20 miles. In 1947, the International Civil Aviation Organization (ICAO) was formed. It adopted the US navigation and communication standard as the worldwide standard and English as the common language for air traffic control. The most important development of this period was the radio detection and ranging (radar) device. The postwar era saw the development of direct controller/pilot interaction, implementation of the VHF omnidirectional range (VOR) and distance measuring equipment (DME), installation of the instrument landing system (ILS) for pilot aiding during landing, and application of radar for surveillance in the airport areas.

The fourth phase of ATM development occurred during 1955 to 1965. A short-range air navigation system known as the VORTAC system was developed by colocating the civilian VOR and the US Navy developed tactical air navigation (TACAN) system in common facilities. Experience with radar use during the postwar era eventually led to the development of air route surveillance radar (ARSR). The first such system was installed at the Indianapolis Center in 1956. In the same year, the first air traffic control computer was also installed at the Indianapolis Center. Research and development efforts were begun by the CAA for a secondary radar system that would use a ground interrogator to trigger transponders onboard the aircraft and obtain replies to display the aircraft identification and altitude on the controller's radar screen. An experimental version of this system known as the air traffic control radar beacon system (ATCRBS) was implemented in 1957. In 1958 the US Congress passed the Federal Aviation Act which created the Federal Aviation Agency as the new independent agency to succeed the CAA. Due to the acceptance of radar surveillance as the principal tool for control of air traffic, new separation standards were needed. Other significant changes during this period were the introduction of high-speed commercial jet aircraft and increase in traffic volume. To accommodate these developments and to keep the task of ATM manageable, smaller segments of airspace known as sectors were developed based on air traffic flow patterns and controller workload considerations. To reduce the workload associated with bookkeeping caused by sectorization, a computerized flight information system for updating flight information and automatically printing flight progress strips was developed. By 1963 several of the flight data processing (FDP) computers were placed into operational ATM service. The first prototype of a computerized radar system for arrival and departure control called the automated radar terminal system (ARTS) was installed in the Atlanta, Georgia, air traffic control tower in 1964. In addition to the steady

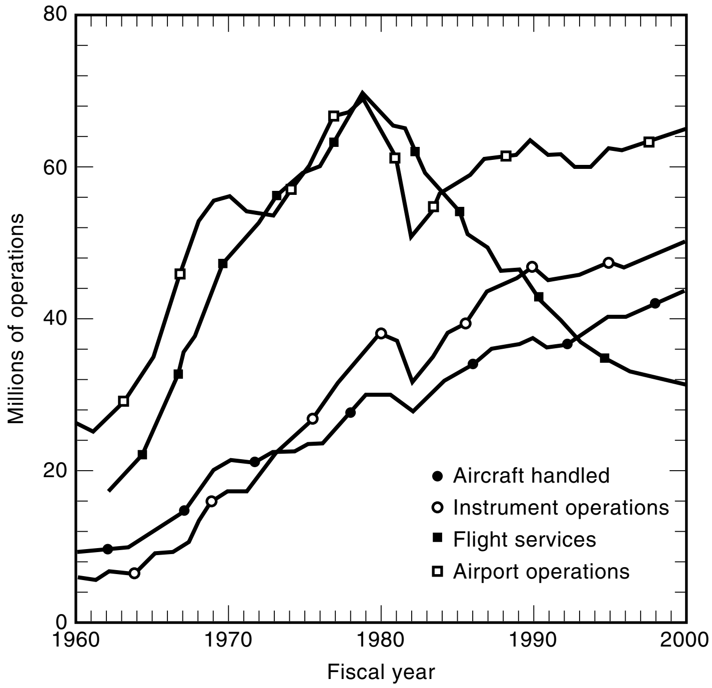

Figure 2. Air traffic activity historical data.

progress toward automation, this period of ATM development saw the air traffic controllers get organized as a union called the Professional Air Traffic Controllers Organization (PATCO).

The fifth phase of ATM development spans the period from 1965 to the late 1990s. Several administrative changes have taken place during this period. The Department of Transportation (DOT) was created in 1967, and the Federal Aviation Agency was brought under its wings as the Federal Aviation Administration (FAA). The National Transportation Safety Board (NTSB) was created to investigate transportation accidents and report its findings to the Secretary of Transportation. This phase of ATM development has also seen numerous technological changes. Alongside the FDP system for flight data processing, a second system called the radar data processing (RDP) system was developed for integrating information from multiple radar sites, automatic aircraft tracking, and handoff capabilities. The RDP system was implemented in all the ARTCCs by 1974. Both the FDP and RDP systems are parts of the ARTCC host computer. Major terminal facilities upgrade has included the installation of the ARTS-IIIA systems which are capable of tracking both transponder equipped and nonequipped aircraft. ARTS-II and en route ARTS (EARTS) versions of the ARTS system were also developed for low- and medium-activity facilities. Other changes of major significance during this period are the Airline Deregulation Act of 1978, the air traffic controllers strike of 1981 that led to massive firing of air traffic controllers by President Ronald Reagan, and the formation of a new union called the National Air Traffic Controllers Association (NATCA) in 1987. The Airline Deregulation Act made it possible for the airlines to determine their own fare and route structures without government approval. The unprecedented growth that resulted put a strain on the ATM system. For operational advantages, the airlines adopted a hub-and-spoke system that overwhelmed the system at some airports. Flow control measures such as ground holding and airborne holding were put into practice for matching the traffic rate with airport acceptance rate.

The traffic growth starting from the middle of the fourth phase of the ATM development to the present is shown in Fig. 2. The graphs in the figure are based on the data provided in the FAA Air Traffic Activity report (4), FAA Aviation Forecasts publication (5), and the FAA *Administrator's Fact Book* (6). It should be noted that the number of airport operations is representative of usage by all aircraft operators including general aviation while the aircraft handled is representative of higher-altitude traffic reported by the ARTCCs. Several interesting trends can be observed from the graphs: traffic growth subsequent to the Airline Deregulation Act of 1978, traffic decline after the PATCO strike in 1981, and the eventual recovery after approximately 3 years. All the graphs except the one for flight service usage show an increasing trend. The decreasing trend in the flight service usage since 1979 is due to (a) improved cockpit equippage, with part of the service being provided by the airline operations centers (AOCs), and (b) consolidation of the FAA flight service facilities.

OPERATIONS WITHIN THE ATM SYSTEM

Flight operation within the current ATM system is described via an example flight from the San Francisco International Airport to the Los Angeles International Airport. Some of the facilities that provide separation and flow control services to this flight are shown in Fig. 3. The dashed lines show that the aircraft is tracked by the primary radar and the secondary radar beacon system during the aircraft's flight through the TRACON and ARTCC airspaces. The airport surveillance radars (ASRs) provide information to the TRACONs, and the air route surveillance radars (ARSRs) provide information to the ARTCCs. The surveillance data along with the filed flight plan provide the information for decision-making to enable safe and efficient flight operations within the airspace.

In preparation for the flight, the pilot of the aircraft contacts the Oakland Automated Flight Service Station located in Oakland, California, and furnishes the following flight plan information: type of flight such as VFR or IFR, aircraft identification or pilot's name, aircraft type such as LJ23 for Learjet 23, departure point such as KSFO, estimated time of departure, altitude, route-of-flight, destination such as KLAX, and the estimated time en route. Based on this information, the air traffic control specialist briefs the pilot. The standard briefing includes current or forecast conditions which may adversely impact the planned flight, a recommendation for VFR flight, a synopsis of weather systems affecting the flight, current weather conditions, en route forecast, a destination forecast, winds aloft forecast, notices to airmen, and ATC delays for IFR flights. In addition to the standard briefing, the pilot can request an abbreviated briefing for updated forecasts and outlook briefing for a planned flight more than 6 hours away. In the case of airline pilots, the weather briefing is provided by the airline dispatcher. On completion of the weather briefing, the flight service specialist enters the flight plan data into the FSS computer. The computer sends the flight plan information to the host computer at the departure ARTCC which for this flight is Oakland ARTCC located in

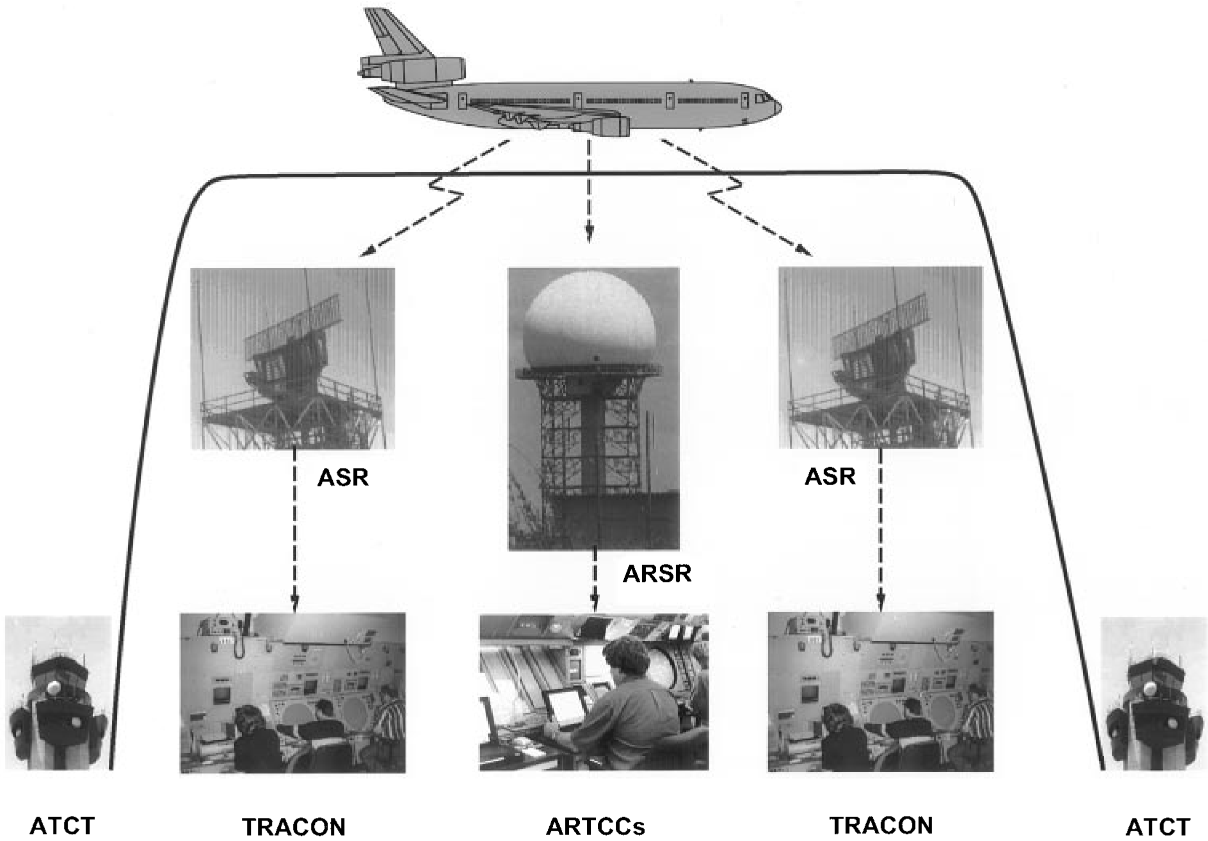

Figure 3. Air traffic control process.

Fremont, California. The flight plan entered into the airline host computer by the airline dispatcher is also sent to the host computer at the ARTCC via the aeronautical data network system (ADNS).

The ARTCC host computer checks if preferred routings are applicable to the proposed flight plan. If they are, the flight plan is modified. Thirty minutes prior to the proposed departure from San Francisco International, the flight plan is activated, a transponder code is assigned to the aircraft, and the flight plan data are transmitted from the ARTCC host computer to the ARTS computer at the Bay TRACON located in Oakland, California. Flight plan activation also causes a flight progress strip to be printed at the clearance delivery position in the tower cab at San Francisco International.

When the pilot is ready to depart, the pilot contacts the clearance delivery controller at the assigned frequency. The clearance delivery controller confirms that the printed flight progress strip conforms with the letter of agreement between the San Francisco Tower and the Bay TRACON. If changes to the route or altitude are needed, they are entered into the flight data input output (FDIO) system. Based on the facility directives, the clearance delivery controller initially assigns an altitude that is delegated to the local controller. This area is known as the departure fan (1). The clearance delivery controller communicates the complete clearance including the restrictions and the departure frequency to the pilot. The flight progress strip is passed to the ground controller. There is also an automated clearance delivery process known as the predeparture clearance that is available to airlines. The clearance input from the FDIO system in the tower is sent to the ARTCC host computer which reroutes it to the airline host computer via ADNS. The airline host computer then delivers the clearance to the aircraft communications, addressing, and reporting system (ACARS) in the cockpit or to the gate printer.

Once clearance is received, the pilot contacts the ground controller in the tower cab for taxi instructions to the active runway. The ground controller is responsible for separation of aircraft and vehicles on airport movement areas except the active runways. Thus, the ground controller issues instructions to the pilot to safely taxi to the active runway. The ground controller coordinates with the local controller if the aircraft has to cross any active runway.

The pilot then contacts the local controller, also referred to as "tower" controller. The local controller sequences this flight into the local flow while ensuring that the aircraft will not be in conflict with the other inbound and outbound aircraft. Next, the local controller instructs the pilot to contact the departure controller at the Bay TRACON.

As soon as the ARTS computer at the Bay TRACON detects this flight's transponder transmissions, it sends a departure message to the host computer at the Oakland ARTCC. The departure controller radar identifies the aircraft and verifies the accuracy of the readout provided by the aircraft's transponder. Subsequently, the controller advises the pilot that radar contact has been established and authorizes the aircraft to climb to the requested altitude. The controller also vectors the aircraft to join the proper airway. During the initial climb phase, the departure controller is responsible for separating this aircraft from all other aircraft in the vicinity.

The departure controller initiates a handoff with the Oakland ARTCC before the aircraft leaves the Bay TRACON boundary.

Radio contact with the Oakland ARTCC is established before the aircraft enters the ARTCC airspace. The ARSR detects the aircraft and sends the position information to the ARTCC host computer. The host computer uses the flight plan information and the aircraft position information to track the aircraft and display the aircraft's position, identification, altitude, and groundspeed on the controller's plan view display (PVD). Using the displayed information and the decision support tools, the controller provides separation services to the aircraft within the sector airspace. As the aircraft climbs from lower to higher altitudes, it is handed off from the low-altitude sector controller to the high-altitude sector controller and then from one high-altitude sector controller to the next until the aircraft nears the ARTCC boundary. It is then handed off to the Los Angeles ARTCC located in Palmdale, California.

The Los Angeles ARTCC host computer activates the flight plan about 30 min before the aircraft is scheduled to enter the ARTCC airspace, and the flight progress strip is printed for the sector controller who would receive the handoff. Once the aircraft is automatically handed off by the Oakland Center, the sector controller verifies the accuracy of the altitude readout from the aircraft's transponder and issues the altimeter setting from the closest airport equipped with a weather observer. The aircraft is continuously tracked by the ARTCC host computer using the ARSR. Separation services are provided by the sector controllers as the aircraft flies from one sector to the next. As the aircraft nears its destination, the Los Angeles high-altitude sector controller initiates a descent clearance to transition the aircraft to the TRACON. Control is transferred from high-altitude controllers to low-altitude controllers until it nears the boundary of the Southern California TRACON located in San Diego, California. At this point, the pilot is instructed to contact the approach control at Southern California TRACON.

The flight information from the host computer in the Los Angeles ARTCC is sent to the Southern California TRACON about 30 minutes in advance to prepare for the aircraft's arrival. As the aircraft enters the TRACON airspace, it is tracked by the ARTS computer and the information is displayed on the controller's plan position indicator (PPI). Once the handoff is accepted by the approach controller, the aircraft is constrained to continue descent within the confines of the airspace allocated to the approach controller. The approach controller vectors the aircraft to position it for easy transition to the ILS aproach course. The pilot is then cleared for the ILS approach and advised to contact the local controller at the Los Angeles International ATCT and report crossing the final approach fix.

Beyond the final aproach fix, the local controller assumes responsibility for sequencing the aircraft into the inbound traffic flow and ensuring the aircraft flight path is conflict free all the way to the touchdown point on the airport surface. The local controller instructs the pilot that the aircraft is cleared to land. After landing, the local controller instructs the pilot to contact the ground controller for taxi instructions to the parking area. The ground controller issues taxi instructions to the pilot and monitors the movement of the aircraft from the tower cab. In reduced visibility conditions, the movement is monitored on a radar display driven by the airport surface detection equipment (ASDE).

FUTURE ATM DEVELOPMENTS

The future ATM system will be based on collaboration between the cockpit, airline operations centers, Central Flow Control Facility, ARTCCs, TRACONs, and ATCTs. This will be enabled using satellite-based navigation and surveillance systems, datalink technologies, and decision support tools on the ground and in the cockpit. Aircraft would be intelligent data collection and information processing agents and would actively participate in the flow management and separation functions of ATM.

The motivations for collaborative ATM are improved safety and economy. Traditionally, the ATM system has been mainly focused on safety. Both the flow management and separation functions are geared toward safety. Flow control is applied in an anticipatory and strategic way to prevent overwhelming the system, and separation minimums are applied tactically to prevent aircraft from getting close to each other. Successful application of these methods is dependent on the predictability of traffic which is derived from knowledge about the intent of the aircraft, their current states, their capabilities, and their operational procedures. The longer-term intent information is provided by the filed flight plan which consists of segments within the fixed route structure, while the shorter-term intent information is obtained by maintaining the track data received from the primary and secondary surveillance radar systems.

The airline operators and pilots are interested in the most economical flight operations under the cover of safety provided by the ATM system. Many of their aircraft are equipped with onboard navigation aids which provide the freedom from being constrained to operate on the airway routes where ground-based navigation aids are available. They want to use their navigation ability to fly routes of their choice including shortest distance or wind optimal routes. It is estimated that US airlines incur a loss of $5.5 billion annually due to operations under the current procedures (7). The users also want to be able to negotiate with each other to fly the route of their choice. The challenge for the future ATM system is to allow the user preferences while preserving the predictability of traffic so as not to compromise safety. It is envisioned that in this flexible ATM environment, restrictions would be limited in extent and duration to correct the identified problem. Intermittent positive control would be applied by the ATM system to ensure separation, to preclude exceeding airport capacity, to prevent unauthorized flight through special use airspace, and to ensure safety of flight. This concept has come to be known as the free flight concept (8). The technologies that will enable the transition from the ground-based ATM system to an air–ground-based ATM system are described next.

Navigation and Surveillance Systems

The global positioning system (GPS) is the emerging navigation system that provides global navigation capability to suitably equipped aircraft. This system, developed by the Department of Defense, is based on a constellation of 24 orbiting satellites that broadcast their positions and the clock time

(9,28). The difference between the time at which the signal is received by the GPS receiver station and the time at which the data were sent by the satellite provides the range with respect to the satellite. These relative positions are used with the broadcast positions to determine the inertial position of the GPS receiver since the broadcast positions are given with respect to an inertial frame of reference. Information from three satellites is adequate for position estimation if the GPS receiver clock is synchronized with the satellite clock or if the altitude is known. By adding information from one more satellite, the GPS receiver clock bias can be removed. Thus, information from four satellites is needed for accurate position determination. The standard positioning service that is available for civil use provides an accuracy of 100 m (328 ft) horizontally 95% of the time and 170 m (560 ft) vertically (10). Accuracies better than 10 m in all three dimensions are available for military use. The positioning accuracy can be significantly improved by using range error corrections broadcast from a ground-based GPS unit located at a surveyed location. This system is known as the differential GPS (DGPS) (9,28). It is also known as the local area augmentation system (LAAS) since it only provides local calibration corrections. An extension of this system is the wide area augmentation system (WAAS), which uses a network of ground-based monitor stations, communications networks, and master stations. The GPS measurements taken by the monitor stations are sent to the master stations where error corrections are computed using the known locations of the monitor stations. The error corrections are uplinked to the airborne system using a satellite, radio, or telephone datalink.

The GPS-based technologies will enable precise en route/terminal area navigation, approach, and landing (11). Accurate area navigation may lead to a more efficient structuring of the airspace and reduction of the separation minimums. In the future it will be possible to transmit the information derived from the airborne GPS or other navigation systems to the ground via a satellite datalink. These data will provide an additional source of surveillance information for the ATM system. The concept for transmitting the aircraft position information to the ATM system is known as automatic dependent surveillance (ADS) (7,28). ADS will significantly impact oceanic ATM since radar coverage is unavailable over the oceans. Accurate surveillance information will allow a reduction of oceanic ATM separation minimums and bring the service standards in line with what is available over the continental United States. Such a system would also improve the safety of domestic flight operations by providing backup surveillance information during radar system outages. A broadcast version of the ADS known as ADS-broadcast (ADS-B) is also under development. In addition to providing the basic ADS capabilities, this system is intended for broadcasting the aircraft's position so that it can be read and displayed in the cockpits of nearby aircraft (7). This system is also expected to aid the air-to-air and air–ground cooperative decision-making process. ADS is also envisioned to be the surveillance system of choice for other countries that do not yet have the kind of radar coverage as in the United States.

Communications

The communications system of the future is expected to shift from being largely voice-based to datalink-based (7,28). One of the drivers for this change is frequency congestion at busy facilities where controllers are constantly in voice communication with several aircraft with little time left for standard readback of clearance information. The promise of datalink is that standard information such as speed, altitude, and heading assignments along with changes entered by the controller can be quickly sent to the cockpit. Several different design options are being considered (7). The first option is to send the information from the ARTCC host computer to the airline host computer via the aeronautical data network system which would route the information to the cockpit using the already available ACARS service provided by Aeronautical Radio Inc. (ARINC). The second option for uplinking data to the cockpit is to communicate with the onboard mode-S transponders. Although the mode-S transponders are capable of selective interrogation and have a built-in datalink capability to support data communication with the ground and similarly equipped aircraft operating in the neighborhood, they are not designed to support large amounts of data transfer. The bandwidth of the ACARS and mode-S systems can be increased to overcome the transfer rate limitations. In addition to these two options, other satellite-based high bandwidth communication systems are also being considered. The improved datalink capability will permit clearance delivery, data exchange, and even negotiation of complete flight segments between ATC and cockpit.

As data communication increases, voice will be used predominantly for checks and confirmations. For example, the pilot would verbally confirm to the controller that the clearance has been received rather than reading back the clearance. The complete clearance could be digitally transmitted back to ground for record-keeping and verification purposes. Increased use of datalink and the reduced role of voice communications is not without human factor concerns. Pilots are aware of the traffic situation by listening to the communication between other pilots and controllers. The voice system therefore provides yet another safety net for flight operations. Other concerns are related to cockpit workload increase caused by the need to interpret large amounts of displayed data sent using the datalinks and boredom caused by the lack of aural stimulus. Boredom added to the natural tendency to sleep during the nighttime hours has safety implications for nighttime flight operations.

Weather Prediction Systems

Approximately 40% of aviation accidents are attributed to adverse weather conditions (12). Weather is the largest single contributor to traffic flow problems. It is also the least predictable. Although advances have been made in weather processing, adequate sensor coverage has not been available to provide the spatial and temporal scale of weather observations needed for accurate short-term predictions. Since most flights are completed within 2 h, the focus is on events that occur on a 0 to 2 h time scale and within a 50 mi (80 km) space scale. This spatiotemporal scale is known as mesoscale (12).

To enable mesoscale predictions, a national network of Doppler weather radars is being developed. This network, known as the next generation radar (NEXRAD) network, is designed for wide-area surveillance and detection of weather phenomena in the en route areas. A special-use Doppler radar termed terminal doppler weather radar (TDWR) has been developed to provide windshear data within the terminal areas. This system will be integrated with the low-level windshear alert system (LLWAS) to enhance the weather prediction accuracy (12,13). LLWAS uses direct anemometer measurements. Plans have been made to field automated surface weather observing systems at small and medium-sized airports. This system, known as the automated weather observing system (AWOS), is designed to provide data to the national observation network. Traditionally, vertical wind profiling data consisting of windspeed, temperature, pressure, and humidity aloft have been measured by launching balloon systems from widely distant locations. In the future vertical wind profiling will be done using a microwave Doppler system. An important resource for aviation weather is the wind and temperature data observed by thousands of aircraft for navigation and performance monitoring. Some airlines already have their flights provide wind and temperature data periodically via ACARS downlink. As datalink technologies mature, it will be possible to collect the airborne observation data in large databases to augment the data collected by the ground-based observation systems. Access to airborne observation data will enable identification of turbulence regions which are usually much smaller than what can be predicted using the ground-based systems (12). Finally, improved weather observations will also be available from weather satellite systems using radar and radiometer measurements of winds, temperature, humidity, and precipitation.

In addition to the enhancements in the weather sensor systems, the computational and information processing algorithms are also expected to improve. Computational algorithms will make short-term forecasts (nowcasts) possible within 10 min of thunderstorm formation by detecting temperature and moisture boundaries in the observation data. The currently available weather systems that generate large amounts of data which the aviation user has to sort through to obtain the needed facts will be replaced by rule-based weather information systems (12). These systems will provide precise weather messages in contrast with the often lengthy and ambiguous weather briefings provided by the presently available systems.

Decision Support Systems

As progress is made toward a more cooperative and flexible air traffic environment, the biggest challenge for ATM is to improve or at least retain the current levels of safety. Currently, safety is defined in terms of separation requirements. Lateral separation is maintained largely by constraining the traffic to fly on fixed airways. Vertical separation is achieved by constraining the aircraft to fly at assigned altitudes. Longitudinal separation is maintained by ensuring that the aircraft on the same airway are separated by a physical distance as a function of the relative speed of the aircraft, their location with respect to the surveillance radar, and their weight class. The path constraints make the traffic movement predictable, which in turn makes it possible to identify separation violations that are likely to occur in the future. In a flexible air traffic environment with few constraints on traffic movement, decision support systems will be needed for achieving the same or better levels of predictability. These systems will predict the future positions of the aircraft, check if they would violate the separation minimums in advance, and provide conflict resolution options to the controller.

Advanced automation systems such as Automated En Route Air Traffic Control (AERA) system and the Center-TRACON Automation System (CTAS) that are under development use trajectory prediction methods for providing the data needed for conflict detection, conflict resolution and traffic management (14,15). The trajectory prediction process involves using the knowledge of the present states and performance characteristics of the aircraft along with the intent information to determine how the states would evolve along the intended path. Factors that influence trajectory prediction are atmospheric conditions such as ambient temperature and wind velocity, the capabilities of the onboard navigation equipment, and the piloting strategies (16). The type and accuracy of the navigation equipment directly translates into how precisely the aircraft is able to maintain track with reference to its desired course. Piloting strategies such as flying a constant airspeed, an average groundspeed, or attempting to reach a particular location at a fixed time directly influence the along-track position of the aircraft. In the future with advances in datalink technologies, shorter-term intent information consisting of waypoints provided periodically by the aircraft operators may be acceptable in lieu of the long-term flight plan. The data-linked information consisting of the state of the aircraft, measured wind velocity, and ambient temperature is expected to improve prediction accuracy. Along with the advancement of longer-term prediction techniques that are needed for strategic planning and conflict resolution, improvement of shorter-term trajectory prediction methods will support tactical conflict detection and resolution needed to support free flight.

Short-term trajectory prediction is based solely on the knowledge of the present state of the aircraft. Knowledge of the flight plan and weather are not needed. The prediction method consists of propagating the states of the aircraft from the present to a short time into the future by assuming that aircraft controls are fixed for the duration of prediction. For example, a constant turn rate is assumed for the aircraft in a turn. Currently, short-term trajectory prediction is done by the ARTCC host computer software and can be graphically displayed as a trend vector on the air traffic controller's plan view display (PVD) (17). Controllers can use the trend vectors to detect conflicts. The host computer program also detects conflicts that are likely to occur within 3 min based on the predicted trajectories.

A feature of the decision support systems of the future will be the ability to detect conflicts with high reliability. The conflict detection process consists of checking if two or more aircraft will be within a small region at the same time. Several different algorithms are available for this task. Conflict detection can be done by using the brute-force method of comparing every pair of aircraft trajectories at each time instant along their entire length. This method is computationally intensive, and therefore the brute-force method has been combined with heuristics. Several heuristics are used for eliminating most trajectory combinations, and the brute-force method is applied on the remaining trajectories (18). Very efficient sorting-based methods have also been developed for conflict detection (19). Efficiency of conflict detection methods is important because they are used often for examination of the planning and conflict resolution alternatives.

In addition to decision-aiding for the air traffic control function, advanced automation systems will aid the traffic planning process. These systems will use the predicted trajectories to identify regions of high traffic density, forecast center/sector workload, and assist controllers in scheduling traffic into an airport to optimally utilize the available capacity. Some of these capabilities are already available within the Enhanced Traffic Management System (ETMS) that uses strategic prediction of traffic volume for its monitor/alert function (8). It has been suggested that this function should be extended to include measures of sector complexity and controller workload. As the traffic demand continues to grow and nonairway direct routes or wind optimal routes are flown, methods for predicting sector and center workload will be crucial for managing the air traffic operations. Since center/sector complexity is related to the level of difficulty experienced by the controllers, automation systems will utilize structural and flow complexity mesures for aiding the traffic management staff in resource planning, rerouting, and examining alternative airspace configurations.

Human Factors

ATM is a complex interaction between sensors, computers, and communications with humans as decision makers. Controllers and supervisors in all air traffic control facilities share each others' work, supervise it, and provide assistance for safety and efficiency (20). The workspace and the computer interface are designed so that other controllers can easily assess the traffic situation and take over the control position. With the evolution of automation systems, the trends are toward the individual controller interacting more with the automation system and less with other controllers (20). The preferences and choices of individual controllers may make the system less understandable to others, thus making it difficult for other controllers to provide assistance or assume control. Automation will need to provide for easy access to the individual controllers preferences so that other controllers are able to analyze the traffic situation and make a smooth transition into the control position.

The development of automation systems will have to be guided by correct assumptions about controller's knowledge and ability and the air traffic control procedures. The current trends have been to automate mundane and routine tasks such as data entry and updating of information while leaving tasks that require human ingenuity to the humans in the control loop. In the future, advanced decision aids will generate choices for the controller and also assist the controller in evaluating the outcome of a particular control choice. For example, if the controller wishes to investigate whether a change of heading of the aircraft will resolve a predicted separation violation, the automation system will build the proposed trajectory and compare it against all other trajectories to determine if the proposed resolution would resolve the conflict. Both providing choices and testing choices have human factors implications. In the first case, if the controller makes decisions based solely on the choices presented, the controller may eventually lose the skills needed for generating alternative solutions. In the second case when the controller examines the alternatives using automation, the controller may lose the analytical skills needed for assessing possible situations that may result as a consequence of a particular choice. Preventing loss of crucial traffic control skills will have to be a part of the design criteria for future automation systems. As the tools move from a monitoring role to a decision-aiding role, they have to be designed with additional safety features. In addition, the tools should be designed to degrade gracefully such that the controller is able to smoothly transition in the event of a failure.

New human factors issues will need to be addressed as ATM transitions from a centrally controlled and managed system to a distributed system where the cockpit and the airline operations centers participate in the control and management functions. The automation systems will have to keep all the participants involved in the control loop so that they are knowledgeable about the traffic situation. Traffic situation displays and automation systems will have to be provided in the cockpit to inform the crew of the traffic in the neighborhood and to enable them to plan and coordinate flight path changes with crews of other aircraft. The traffic monitoring, management, and separation responsibilities in the cockpit may increase the crew workload. This is especially significant because the number of crew members is expected to decrease and assisting each other to solve traffic problems may detract them from their piloting and flight management responsibilities. Shared traffic control and management responsibilities with the cockpit has the potential for increased controller workload caused by the communications needed for cooperative resolution of traffic situations.

One of the reasons for increasing automation in the ATM system has been to maintain the controller workload with traffic growth. Airspace sectorization and procedure development have also been guided by workload considerations. Additionally, traffic management decisions are influenced by controller workload assessments. For example, the monitor/alert function of the Enhanced Traffic Management System is based on a traffic volume threshold that is acceptable with regard to controller workload. Research on controller workload has been motivated by a desire to understand occupational stress, reduce operational errors, enhance safety, task performance, and efficiency, and improve controller training. Three distinct approaches have been employed for workload research. The first technique attempts to measure the physiological state of the air traffic controller. Measurements of this type have included galvanic skin response (GSR), heart rate, electrocardiogram (ECG), blood pressure, biochemical analysis of body fluids, and behavioral symptoms (21). The second method attempts to measure the controller workload in terms of the physical interactions with the human–computer interface system. Measurements of this type include number of keystrokes, slew ball entries, and communications per unit of time (22). Since the job of air traffic control is primarily cognitive and information-intensive, rather than physical and labor-intensive, the third method attempts to measure the psychological state of the air traffic controller. Workload is measured in terms of the cognitive demand of the task and the available mental capacity (23).

Each of the three methods of workload research has its limitations. The first method based on physiological measurements has had limited success as an indicator of stress related to workload (21). The main difficulty with the second approach of assessing workload in terms of physical interactions with the human–computer interface system is that it ignores the fact that cognitive workload can be significant.

Reference 24 suggests that the task of maintaining vigilance for critical events such as loss of separation, altitude deviations, VFR pop-ups, incorrect pilot readbacks, and other infrequent events imposes considerable mental workload. The third approach is limited in that the task demand and mental capacity are not related in a straightforward way. The research in Ref. 23 suggests that the relationship between mental capacity and task demand depends on the strategies employed to meet the demand and on the skill in choosing the most efficient strategy in cases where multiple options are available.

Inadequacies of these methods have led to attempts at understanding the cognitive structures employed by the controller. The testing methods have included (a) memory tasks such as traffic drawing and flight strip recall and (b) the assessment task of potential conflicts between aircraft (25). Subjective ratings of how operationally meaningful concepts such as weather, traffic volume, and projected proximity between aircraft are related has been used to determine the conceptual structures for decision-making (26). Research into the cognitive structures employed in air traffic control suggests that controllers use the spatial and temporal traffic patterns rather than the instantaneous position of the aircraft displayed on the controller's workstation (25,26). It is believed that the five cognitive stages that form the bridge between the events and actions are selective attention, perception, situation awareness, planning and decision-making, and action execution (24). The research in Ref. 26 has found that weather is a central concept in the controller's cognitive process because it impacts aircraft routing and imposes flow restrictions. Factors that reduce available airspace such as weather phenomena and special use airspace (SUA) within the sector increase workload. Traffic involving aircraft with vastly different performance characteristics increases controller workload. The establishment procedure for en route sectors calls for sectors to be designed to reduce/prevent the mix of such aircraft (27). Mixed traffic could be an issue as the ATM transitions into a more flexible environment. Research indicates that situation awareness is more difficult in crowded, complex, and heterogeneous airspace (24). Further research is expected to result in traffic pattern recognition algorithms that will use traffic data to predict controller workload. Once these algorithms are calibrated against the ratings provided by the controllers, it will be possible to use them for ATM functions.

GLOBAL ATM

Although ATM has been discussed in terms of the domestic air traffic operations within the United States, it is recognized that civic aviation is an international activity. There are 183 International Civil Aviation Organization (ICAO) member nations that are interested in the development of airborne systems, ground systems, standards, and procedures for enabling seamless operations worldwide. For achieving this goal, the ICAO develops standards which are collectively known as the International Standards and Recommended Practices (1). Except for a few minor differences, the ATM system in the United States conforms to the ICAO standards.

The airspace in Europe is shared by several nations, and the 36 member states of the European Civil Aviation Conference (ECAC) have been working toward harmonizing the ATC systems. Eurocontrol, the management organization of the ECAC, has the goal of integrating the ATC systems of various nations toward a uniform European air traffic management system (EATMS). The development of EATMS has to address the diverse needs of all the nations in Europe.

For guiding the development of the future global ATM system, the ICAO has developed a future air navigation system (FANS) concept for communications navigation and surveillance combined with air traffic management (CNS/ATM). ICAO recommends use of VHF radio for voice communications and aeronautical mobile satellite service (AMSS) for both voice and data communications. In high-density areas, mode-S is the datalink system of choice. It calls for the development of a multimode receiver standard for supporting the global navigation satellite system (GNSS), which includes the GPS developed by the United States and the global navigation satellite system (GLONASS) developed by the Russian Federation, instrument landing systems (ILS), and microwave landing system (MLS). In addition to GNSS, the international standard allows the aircraft operator to use navigation equipment that meets the required navigation performance (RNP) requirements in the particular class of airspace. Automatic dependent surveillance (ADS) is slated to be the surveillance system of the future for both domestic and oceanic airspaces. Surveillance information for operations within the terminal area will be provided by the mode-S transponder system. In the future, primary radar will be used for weather only. For collision avoidance, the traffic-alert and collision avoidance system (TCAS) has been in use in the United States, but the ICAO standard which is being developed calls for the aircraft collision avoidance system (ACAS). This system is required to display the locations of the surrounding traffic for situational awareness and for enabling cooperative air–ground decision-making. The future ATM developments in the United States will both influence and be influenced by the ICAO standards.

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