Mode S Data-Link Applications for General Aviation

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■ The Mode S data link is a high-capacity air-ground digital communications system that can deliver information to the cockpit in a form that will significantly improve pilot situational awareness and aircraft utility. The Federal Aviation Administration is currently deploying Mode S surveillance sensors with data-link capability at 143 sites across the United States. Two Mode S data-link applications—Traffic Information Service and Graphical Weather Service—have been developed to meet the specific needs of general aviation. Traffic Information Service uses the surveillance capability inherent in the Mode S sensor to provide the pilot with a display of nearby traffic. Graphical Weather Service provides a means to deliver real-time weather graphics to the cockpit. Additional Mode S data-link applications, including the broadcast of local-area differential corrections for the Global Satellite Navigation System and the use of the Mode S squitter for Automatic Dependent Surveillance Broadcast, also offer significant benefits to general aviation. Low-cost avionics have been developed to support these and other Mode S data-link applications for general aviation.

Among the most important information that affects the situational awareness of pilots of both commercial transport aircraft and general aviation (GA) aircraft is the relative location of nearby aircraft and the location and severity of hazardous weather. The Mode Select (Mode S) data link has the capability to provide this weather and traffic information directly to the pilot. Low-cost Mode S data-link avionics and their associated data-link applications in combination with the Mode S data link offer the potential to improve the safe utility of GA aircraft.

The flight crews of commercial transport aircraft have a variety of on-board systems to assist them with maintaining situational awareness of nearby traffic and potentially dangerous weather. The Traffic Alert and Collision-Avoidance System (TCAS) provides transport crews with a cockpit display of nearby traffic, and it issues resolution advisories that suggest maneuvers to take to avoid an imminent collision [1]. Another on-board system—airborne weather radar—detects hazardous weather ahead of the aircraft. Dedicated airline dispatchers and staff meteorologists on the ground are also available on a company VHF voice-radio frequency to advise pilots of potential problems. The Aircraft Communications Addressing and Reporting System (ACARS) VHF data link provides the airline crew with text weather products, airline operations information, and pre-departure air traffic control (ATC) clearances. In contrast with the airline crew, the GA pilot faces the demanding task of flying the aircraft, operating the navigation radios, communicating with ATC, and interpreting the verbal weather reports from a Flight Service Station, often without the benefit of a second crew member to share the load, or with any of the supporting technology available to the airline pilot.

Like pilots in commercial transport aircraft, the proficient GA pilot constantly searches for information to support the decision-making process during the flight. For example, ATC communications can be monitored for valuable party-line information pertaining to the current weather or traffic situation. When cockpit work load permits, the pilot can contact a Flight Service Station by voice radio for an update on the weather. An ATC controller can provide verbal reports of nearby traffic and pass along valuable reports from pilots who have been through the weather ahead. Too often, however, these limited sources of information are unavailable. A pilot who is not on an instrument flight plan is least likely to receive voluntary verbal traffic advisories when the traffic is heavy and the ATC controller is busy. When a line of storms passes through the area, the Flight Service Station VHF voice-radio frequencies become saturated with requests for weather information, making it difficult for a GA pilot to obtain an update of the situation. In addition, while a commercial transport pilot may spend only a small fraction of a flight in the region below 10,000 feet where most of the adverse weather is found, a GA pilot typically spends the entire flight there.

The technology currently available to the GA pilot is either costly or limited in capability. For instance, the cost of TCAS avionics exceeds the total value of a typical GA aircraft. Less expensive on-board weather-detection alternatives (e.g., lightning detectors) can provide useful severe-weather information, but they have limited range and accuracy, and they are subject to interference that produces missed detections and false alarms. Because of these limitations, digital air-ground data-link communications can provide a means for the GA pilot to obtain both routine information and safety-critical information in-flight.

In 1992, the FAA organized the Data-Link Operational Requirements Team (DLORT) and gave it the responsibility to develop an operational concept for the introduction of digital data-link communications in the National Airspace System. The DLORT identified a hierarchy of four services that would be provided to pilots by data-link communications; these four services are Air Traffic Management Services, Flight Information Services, Navigation Services, and Surveillance Services. Air Traffic Management Services are defined as the information currently exchanged by voice between air traffic controllers and pilots (such as route clearances and altitude assignments), as well as data-link communications that support future air traffic automation (such as route negotiation and automatic sequencing). Flight Information Services are defined to include weather text and graphics, notices to airmen, and other information that is currently obtained by telephone or voice radio from a Flight Service Station. Navigation Services include the broadcast of differential corrections to the Global Navigation Satellite System (GNSS) to permit precision instrument approaches with satellite navigation to many GA airports. Surveillance Services include traffic information derived from ground-based radar systems and the automatic broadcast of position information by individual aircraft (Automatic Dependent Surveillance Broadcast, or ADS-B). Among these service possibilities, the DLORT selected the following individual services for nationwide implementation in the years 1996 through 2000: Basic Air Traffic Management Services, Basic Text Weather Products, Automatic Downlink of Pilot Weather Reports, Traffic Information, and Weather Graphics.

To be useful for GA, the services above require a digital air-ground data link of sufficient capacity to permit the participation of thousands of aircraft. The required data-link avionics must also be suitable for installation in typical GA aircraft. They must be affordable and easily used in single-pilot flight operations, and data-link applications must be tailored to the flight regimes and specific needs of the GA pilot.

The Mode S Data Link

The Mode S secondary radar-surveillance system includes an integrated, high-capacity, digital data-link function [2]. One hundred thirty-seven Mode S sensors are being deployed nationwide to replace the aging ATC Radar Beacon System (ATCRBS) sensors. Figure 1 illustrates the basic components of the Mode S data link. The Mode S sensor, with its rotating surveillance antenna, is capable of transmitting approximately 1500 bits of data to an aircraft equipped with a Mode S data-link transponder each time the antenna beam passes. A typical Mode S terminal sensor, with a rotation period of approximately five seconds, is capable of delivering an average net data rate of 300 bits/sec to each aircraft within the sensor's 60-nmi range of coverage. In this context, and where it is mentioned elsewhere in this article, net data rate is defined as the actual useful data delivered after all communications protocols and error-protection over-

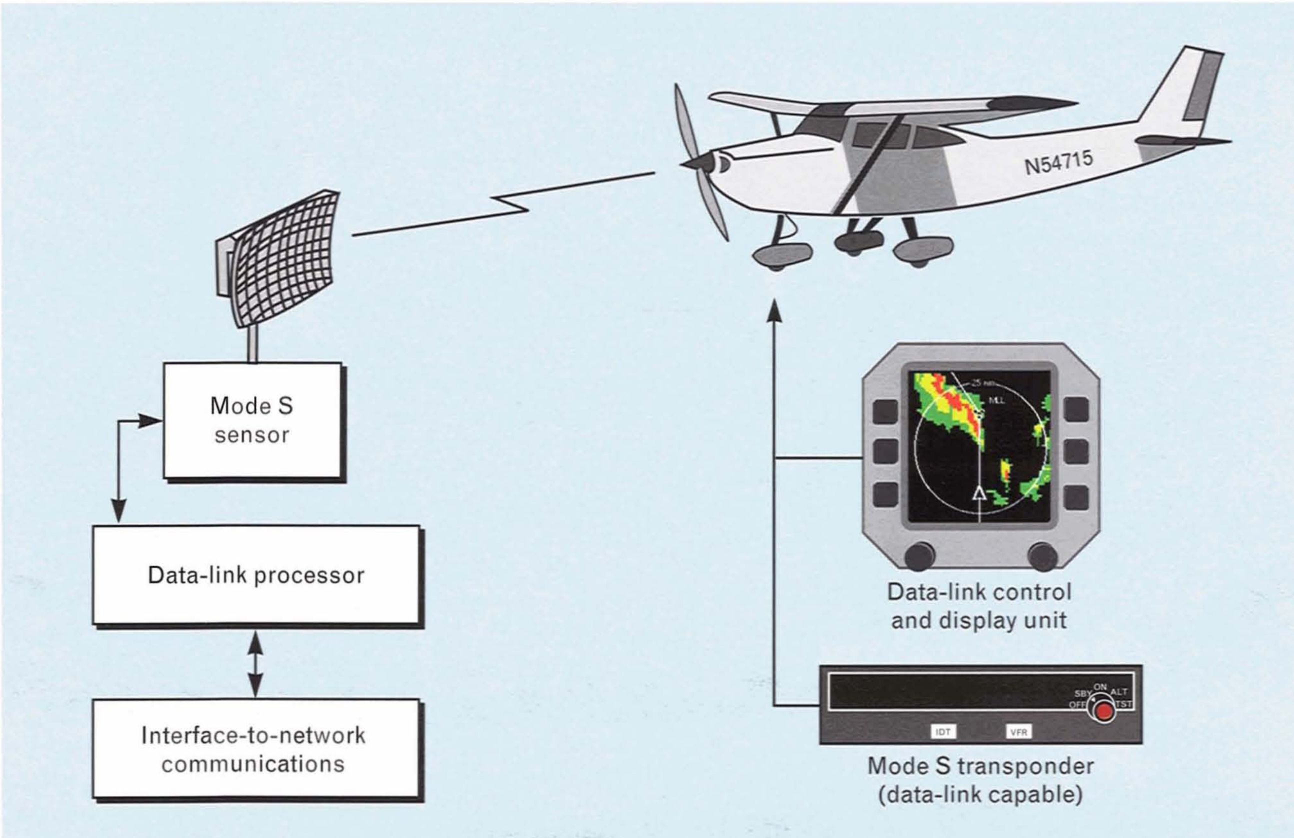

FIGURE 1. Mode S data-link components. The Mode S surveillance sensor provides a connection to ground-based data-link services. The aircraft is equipped with a data-link Mode S transponder and a control and display unit.

head have been removed. For a realistic distribution of aircraft requesting data-link service, a single Mode S sensor is capable of transmitting at a net data rate of more than 60,000 bits/sec [3]. By contrast, the ACARS VHF data link currently in use by the airlines is capable of a net data rate of 600 to 1000 bits/sec. An improved VHF data link, using Aviation VHF Packet Communications (AVPAC) protocols, has been proposed with a net data rate of 5000 to 8000 bits/sec. Thus a single Mode S sensor can deliver as much data as sixty ACARS or eight AVPAC channels.

On the ground side of the data link, the Mode S sensor provides a connection, through a data-link processor, to network communications. The FAA is procuring a ground data-link processor (DLP-II), scheduled for deployment in 1997, that will provide access to the Aeronautical Telecommunications Network (ATN) for services such as ATC communications and text weather products (such as surface observations and terminal forecasts) [4]. In addition to the ATN data-link services, the Mode S data link can also provide services directly to the user without reliance on the ATN communication network. These local data-link services, called Mode S specific services, have the advantages of a lower communications-addressing overhead and do not require modification of the ATN data-link processors and routers for implementation. The two data-link services described below—Traffic Information Service and Graphical Weather Service—are examples of data-link applications that might be deployed initially as Mode S specific services.

The Omnidirectional Mode S Data-Link Ground Station

The deployment of Mode S secondary radar sensors will provide coverage over most of the contiguous airspace of the United States. However, a significant number of smaller airports located some distance from the nearest Mode S sensor will not have coverage below an altitude of approximately 2000 feet. The installation of a standard Mode S surveillance sensor, as shown in Figure 2(a), to provide low-altitude coverage at smaller airports is prohibitively expensive. At these smaller airports a low-cost, omnidirectional, Mode S data-link ground station can be constructed. By taking advantage of data-link features built into production TCAS avionics, Lincoln Laboratory has developed a Ground Interrogator-Receiver Unit (GIRU) that is based on a modified TCAS unit [5]. Connected to a simple omnidirectional antenna and located at a satellite airport, GIRU, which is shown in Figure 2(b), is capable of providing two-way data-link coverage from the airport surface to beyond the extent of coverage of conventional Mode S surveillance sensors [6].

Mode S Data-Link Capacity

Given the large number of GA aircraft operating in the United States, the potential demand for Mode S data-link services is significant. As described above, each terminal-area Mode S surveillance sensor, with its rotating antenna, is capable of delivering an average net data rate of 300 bits/sec to each aircraft within the sensor's 60-nmi coverage radius up to a limit of approximately two hundred aircraft, given a net data rate per sensor of 60,000 bits/sec. (The current design of the Mode S sensor, as deployed, can provide data-link service to a maximum of four hundred aircraft; this limit will be upgraded within approximately one year to seven hundred aircraft.) This aircraft density roughly represents that found in the Los Angeles ba-

(a) (b)

FIGURE 2. Two types of Mode S installations. At left is the rotating antenna of a standard Mode S terminal surveillance sensor. The antenna has a twenty-six-foot span and a rotation period of approximately five seconds. At right is the much smaller Ground Interrogator-Receiver Unit (GIRU), which is suitable for data-link coverage near smaller airports not within the coverage of a Mode S surveillance sensor. The GIRU is shown connected to a standard Distance Measuring Equipment antenna with a height of approximately seven feet.

Table 1. Estimate of the Mode S Data-Link Loading Imposed by a Typical General Aviation Aircraft

Data-Link Services	*Data Content (bits)*	*Update Period*
Weather Graphic	2400	2 min
Weather Text	1200	2 min
ATC Route Clearance	600	2 min
Routine ATC Message	100	2 min
Traffic Information	112	5 sec

sin, which is the region with the highest traffic density in the United States. Typically, aircraft in this congested airspace would be under the coverage of two or more Mode S sensors, so that the actual data-link load seen by any single sensor would be a fraction of its maximum capacity.

Table 1 illustrates the average data-link demand imposed on a Mode S sensor by a GA aircraft. We assume that, during a typical flight, a GA pilot might request a graphical weather image, a text weather message, and an Automatic Terminal Information System message, on average, once every two minutes. In addition, ATC communication would take place in the form of a route clearance and a routine message every two minutes. We also assume that the pilot would require the continuous display of data-link-provided traffic information, receiving an update every five seconds. Estimates of the data content of each message are based on the actual implementation of these services as they are described in the following sections.

Because of the pilot attention required to attend to this significant amount of data-link information, the services and update periods in Table 1 represent a rather conservative (high) estimate of the data-link demand imposed by a GA aircraft. Nevertheless, the total average data rate utilized by the services in Table 1 is 60 bits/sec, which is approximately 20% of the total Mode S data link available to the aircraft, even in the most congested airspace. All of the data-link messages defined in Table 1, with the exception of the weather graphic, can be delivered by a Mode S sensor within a single antenna scan (approximately five seconds). The weather graphic would require two antenna scans (approximately ten seconds).

General Aviation Data-Link Avionics

To receive data-link services, an aircraft must be equipped with the proper avionics. In general, these avionics include a data-link transceiver and a control and display unit (CDU) (see Figure 1), which are analogous to the telephone modem and personal computer used for ground-based digital communications. In the case of the Mode S data link, the function of the data-link transceiver is served by a Mode S transponder. The Mode S transponder duplicates the function of the older ATCRBS transponder by replying to ATCRBS sensor interrogations with the standard four-digit identity code (Mode A) and altitude (Mode C) information [2]. It also replies to the selective interrogations of the Mode S sensor, including those that contain data-link messages. Figure 3 shows a Mode S transponder manufactured for GA use.

The data-link CDU serves as the display and input device for the pilot. Just as in the personal-computer analogy, the data-link communications and applications software resides in the CDU. Among the most challenging human-factors issues associated with GA data-link communications is the design of an appropriate pilot interface for single-pilot operation. The restricted instrument-panel space in a typical GA aircraft limits display size. The challenging physical and mental work-load environment places significant constraints on the design of input devices. Some of

FIGURE 3. Mode S transponders similar to the panel-mount model pictured here, with a retail price of approximately $3000, can provide data-link capability to general aviation (GA) aircraft.

these issues have been addressed by the manufacturers of Global Positioning System (GPS) and Long-Range Navigation System (LORAN) navigation equipment in the design of displays and input devices for navigation databases. The multiple functions provided by data link, however, will impose additional requirements on the design of pilot displays.

Figure 4 shows the installation of a color CDU suitable for data-link applications in the instrument panel of a typical GA aircraft. Although the CDU shown here is based on a color cathode-ray-tube display, recent developments in active-matrix liquid-crystal displays (LCD) have made lower-cost color displays possible for GA aircraft. Estimates of the cost of a production data-link CDU, based on low-cost LCD technology, range from $2000 to $5000, depending upon the complexity of the pilot interface, the size of the display, and the data-link application software that it contains. When combined with the cost of a Mode S data-link transponder, the total estimated cost of data-link avionics for GA aircraft is $5000 to $8000.

Mode S Data-Link Applications

Just as the utility of a personal computer and modem depends upon the applications software and network services available to the user, the utility of the Mode S data link depends upon the services provided to the pilots. Two Mode S data-link applications called Traffic Information Service (TIS) and Graphical Weather Service (GWS) have been developed to address the GA pilot's need for situational awareness of traffic and weather.

Traffic Information Service

The primary method of collision avoidance employed by the pilots of GA aircraft is a constant visual search for traffic; the FAA term for this visual search is "see and avoid." The goal of TIS is to assist the pilot with the task of "see and avoid" by providing an automatic display of nearby traffic, including visual and aural alerts of any traffic that presents a potential collision hazard. The goal of assisting "see and avoid" is identical to that of TCAS-I, the simplest version of TCAS, which provides a display of nearby traffic and collision threats, but does not issue resolution advisory maneuvers to the pilot for collision avoidance.

Figure 5 illustrates the operation of TIS. When performing its function as a secondary radar-surveillance system, the Mode S sensor maintains a surveillance track file (identity, range, azimuth, and altitude) for each transponder-equipped aircraft within its cov-

FIGURE 4. Data-link control and display unit (CDU) as installed in the instrument panel of the Cessna 172 data-link test-bed aircraft. Shown is a color radar precipitation image transmitted to the aircraft by Mode S data link. Color LCD technology shows promise for low-cost data-link CDUs in the \$2000 to \$5000 price range.

erage. TIS consists of a set of software algorithms that reside in one of several redundant surveillance processors within the Mode S sensor. Upon a data-link request from a particular aircraft, the TIS algorithms use the Mode S surveillance track files to determine the relative locations of all of the aircraft within five nautical miles and ±1200-ft altitude of the requesting aircraft. In addition to the relative position of other aircraft, the TIS algorithms determine if the trajectories of those aircraft pose a collision threat to the requesting aircraft. The TIS logic that determines collision threat is similar to that used by TCAS-I. By using the relative range between the requesting aircraft and each of its neighbors, we can compute an alerting parameter τ (where τ = range / –range rate) for each nearby aircraft. Whenever τ is less than thirty seconds, the corresponding aircraft is declared a collision threat. The relative positions of each nearby aircraft and their threat status are sent to the aircraft as a Mode S data-link message. The data are displayed to the pilot by using a standard TCAS-I display format, including an audible alert that accompanies the declaration of a collision threat. The pilot, alerted to the intruding traffic, is able to determine its relative bearing, range, and altitude. With this information, the pilot can concentrate his or her visual search in the proper area, quickly see the traffic, and take appropriate action.

The effectiveness of TIS, or any similar collision-avoidance system that relies on "see and avoid," can be measured by its effect on the pilot's ability to acquire nearby traffic visually. A mathematical model for pilot visual acquisition was developed and has been used to evaluate the performance of TCAS as well as other collision-avoidance systems, including TIS [7]. The TIS traffic display in the cockpit is updated each time the Mode S sensor beam passes the aircraft, which is approximately once every five seconds. Flight tests with pilot subjects in GA aircraft have shown that this update rate is sufficient to result in an approximately eightfold improvement in visual-acquisition efficiency; this level of improvement is equivalent to that demonstrated with TCAS-I. A frequent observation made by pilots who have survived a midair collision is that they were not aware that another aircraft was near them. Beyond simply making visual acquisition more efficient, TIS will significantly help the pilot maintain overall traffic situational awareness.

Because TIS relies on Mode S surveillance information, it operates only in airspace for which there is Mode S surveillance coverage. Though this covered airspace is a significant fraction of the airspace used by GA aircraft, and includes all areas of high traffic density, TIS does not provide total airspace coverage. Despite this limitation, the significant advantage of TIS over other collision-avoidance systems is its relatively low cost (approximately one-tenth the cost of TCAS-I) and the lack of requirement for all other aircraft to be equipped with collision-avoidance equipment for TIS to be effective.

A long-term solution to collision avoidance for GA aircraft is the use of Automatic Dependent Surveillance Broadcast (ADS-B) in which each aircraft automatically broadcasts its own position. The GPS-Squitter system [5], discussed below, is an ADS-B concept that makes use of the Mode S data link. The important advantage of TIS is that it will provide immediate benefit to GA aircraft and a means to make a smooth transition to a collision-avoidance system based on ADS-B in the future.

Graphical Weather Service

The goal of Graphical Weather Service (GWS) is to provide real-time weather information to pilots in a

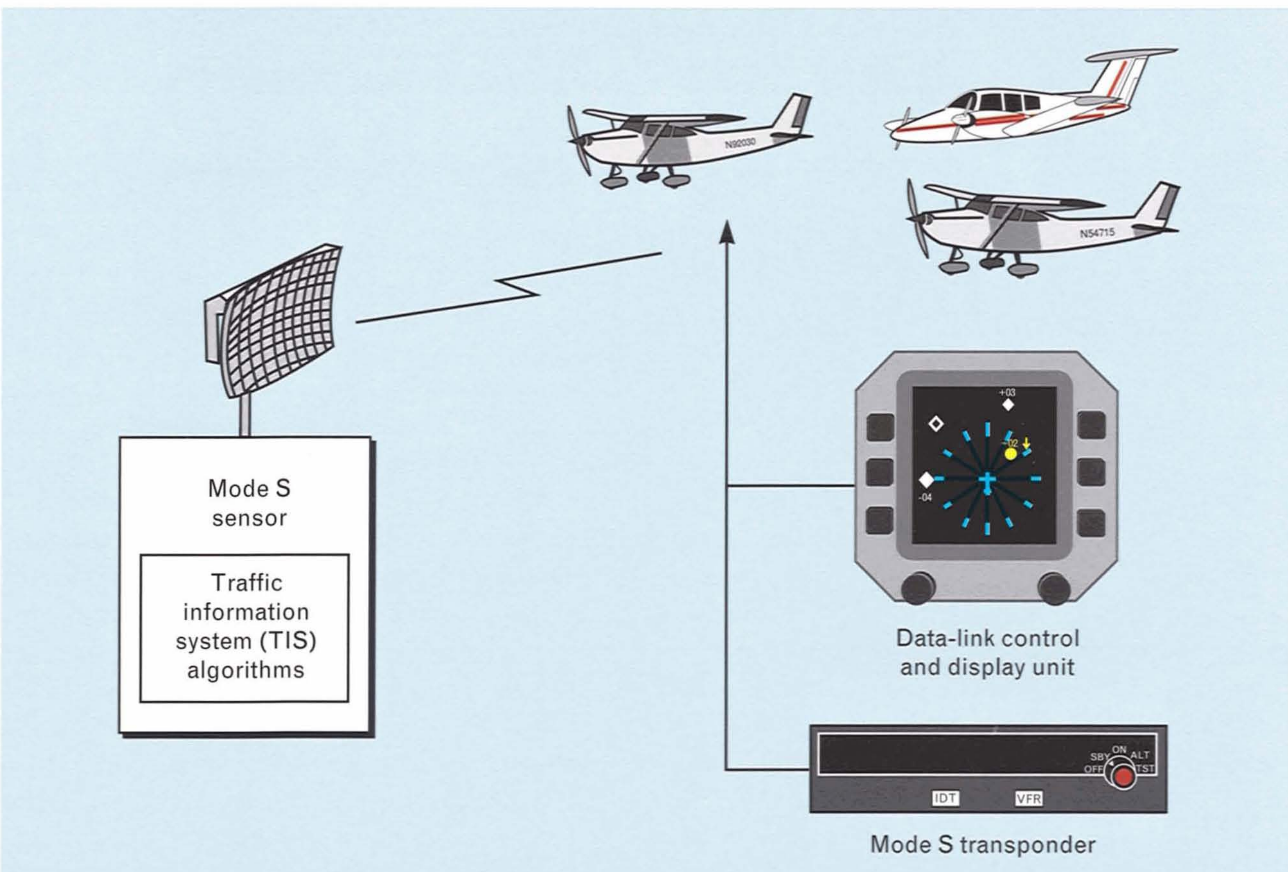

FIGURE 5. Traffic Information Service (TIS). The TIS algorithms operating in the Mode S surveillance sensor at left determine the location of nearby traffic and transmit that information by data link to the requesting aircraft where the information is displayed in the CDU in TCAS-I format. The TIS display is updated during each Mode S antenna scan (approximately every five seconds).

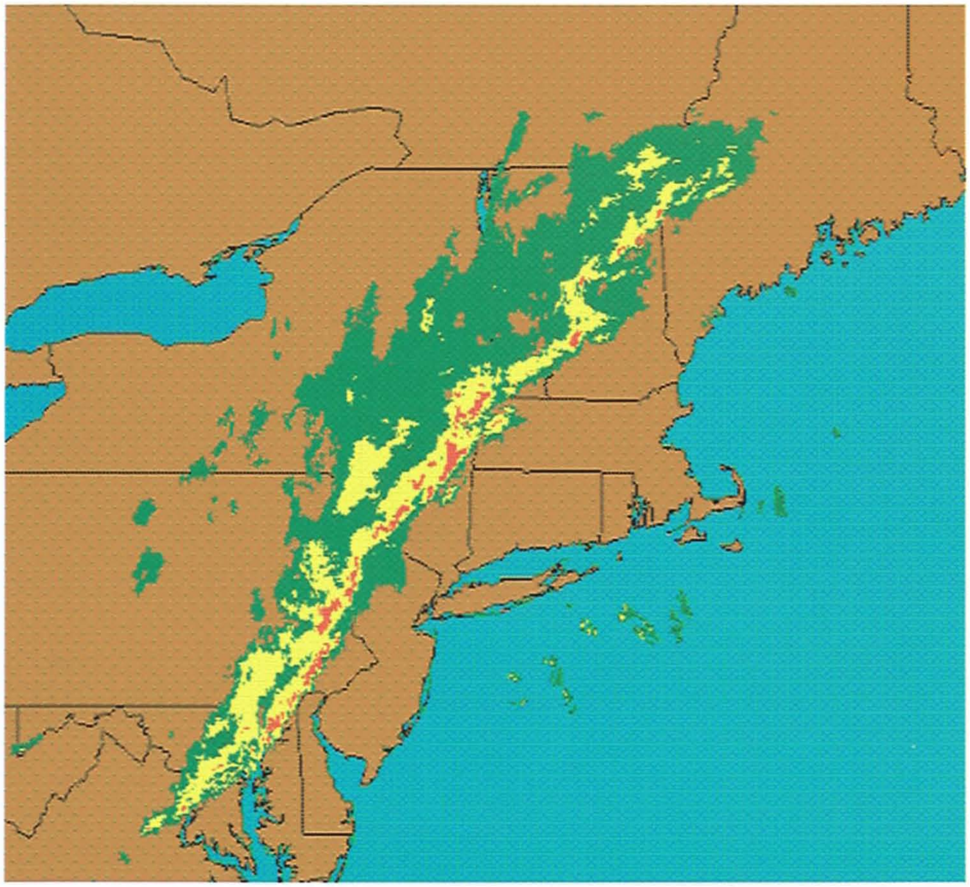

FIGURE 6. Composite radar precipitation image of weather over the northeastern United States. This image, which is a commercial weather product provided by WSI Corporation, is a composite mosaic of data from ground-based weather radars. Light precipitation is shown in green, moderate in yellow, and heavy in red.

form that is both relevant and easily interpreted. While some weather information, such as that found in a typical sequence report or terminal forecast, is adequately expressed in text form, much of the weather of significance to pilots is best presented as a weather graphic. Examples of this kind of weather include regions of precipitation, lightning, icing, low ceiling and visibility, and turbulence. Even though pilots are able to obtain weather graphics of some of these phenomena on the ground by using land-line data communications, the dynamics of weather are such that the situation probably will change by the time the aircraft is in flight.

Figure 6 is a graphical depiction of the precipitation associated with a cold front in the northeastern United States. This image, which is a commercial weather product provided by WSI Corporation, is a composite mosaic of several ground-based weather radars. It is a real-time depiction of precipitation that is updated approximately every fifteen minutes. Such an image is clearly valuable to pilots of GA aircraft, particularly those pilots whose aircraft have limited capability to fly in hazardous weather. This image offers the pilot the information necessary to plan a route around the weather, divert to an alternate airport, or simply to land and wait until the weather improves.

The data-link transmission of the precipitation image depicted in Figure 6 would require a total message size of over 300,000 bits, exclusive of the geographical base map. This message size would require far more bandwidth than is currently available with any practical data-link implementation. A need clearly exists for considerable data compression to permit routine

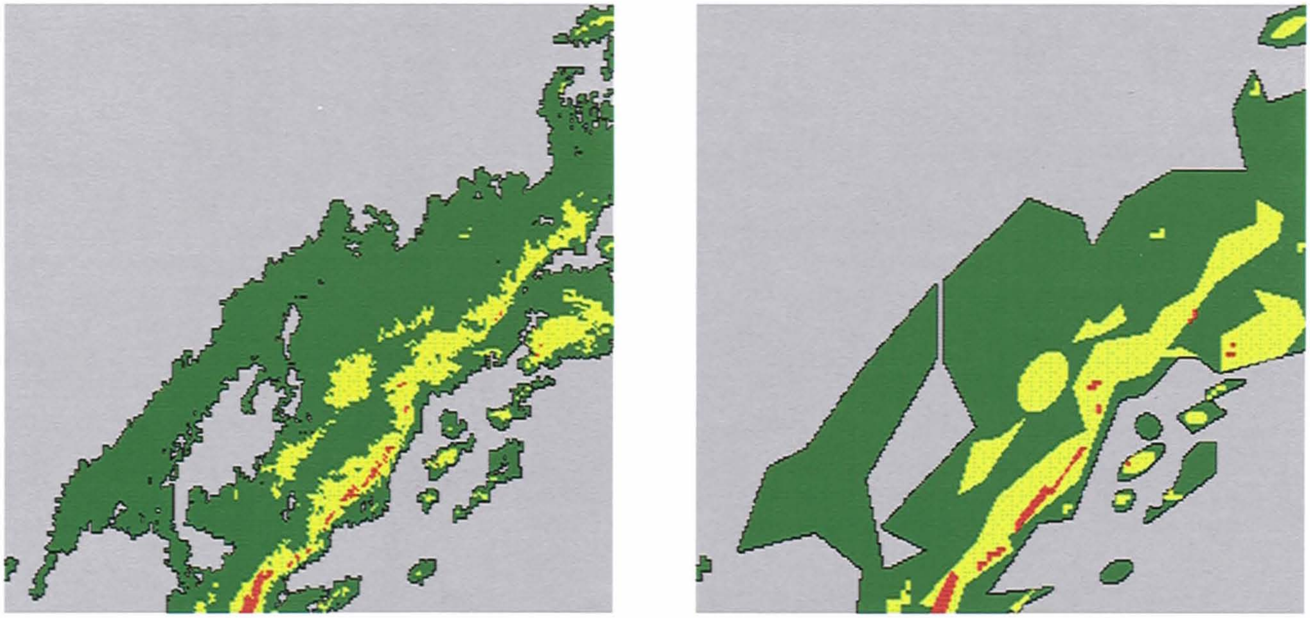

FIGURE 7. Compressed and uncompressed weather-radar images. Without data compression, the 256 × 256-km image at left would require 131,000 bits to transmit. The image at right is compressed to 2413 bits by using the Polygon-Ellipse algorithms. The compressed image can be transmitted to the aircraft by Mode S data link in approximately ten seconds.

transmission of weather graphics to the cockpit. A specialized image-compression algorithm has been developed that maintains the overall morphology of weather images while maintaining reasonable image data size [8]. These algorithms exploit the inherent geometric shape of the weather phenomena by representing them as a series of polygons and ellipses rather than discrete pixels. Instead of transmitting the large amount of data required to describe the individual pixels, the algorithm needs to transmit only the location and shape of the geometric forms that make up the image for reconstruction on the aircraft display. By using the Polygon-Ellipse algorithm, we can take an image that requires 131,000 bits to transmit and reduce it to 2413 bits (as shown in Figure 7), which is a message size that can be transmitted to an aircraft from the rotating antenna of a Mode S surveillance sensor in two scans (roughly ten seconds). Although the GWS has been designed as a Mode S data-link application, its image-compression algorithms can be equally applied to the transmission of weather graphics with any data-link implementation.

As described above, the first generation of ATN ground data-link processors (DLP-II) will have the capability to provide basic ATC communications and text weather products through the Mode S sensor. DLP-II, however, as it is currently planned for deployment, will have no provision for weather graphics. Figure 8 illustrates how the GWS could be implemented as a Mode S–specific service for weather graphics capability in advance of a permanent upgrade to DLP-II. An image-compression processor, implemented in a low-cost commercial computer workstation, is connected to one of the several Mode S sensor data-link ports in parallel to the DLP-II. The image-compression processor, which is connected by land line or satellite link to a commercial or government weather provider, maintains a real-time database of uncompressed weather graphics. Upon a data-link request from an aircraft, the image-compression processor selects graphic imagery of the area of interest from its weather database, compresses the imagery, and passes it to the Mode S sensor for data-link transmission. On board the aircraft, the weather image is decompressed and displayed to the pilot in either track-up format (as shown on the CDU in Figure 8) or north-up format. The weather image can be integrated with navigation information to provide the pilot with a visualization of the weather relative to the proposed route of flight.

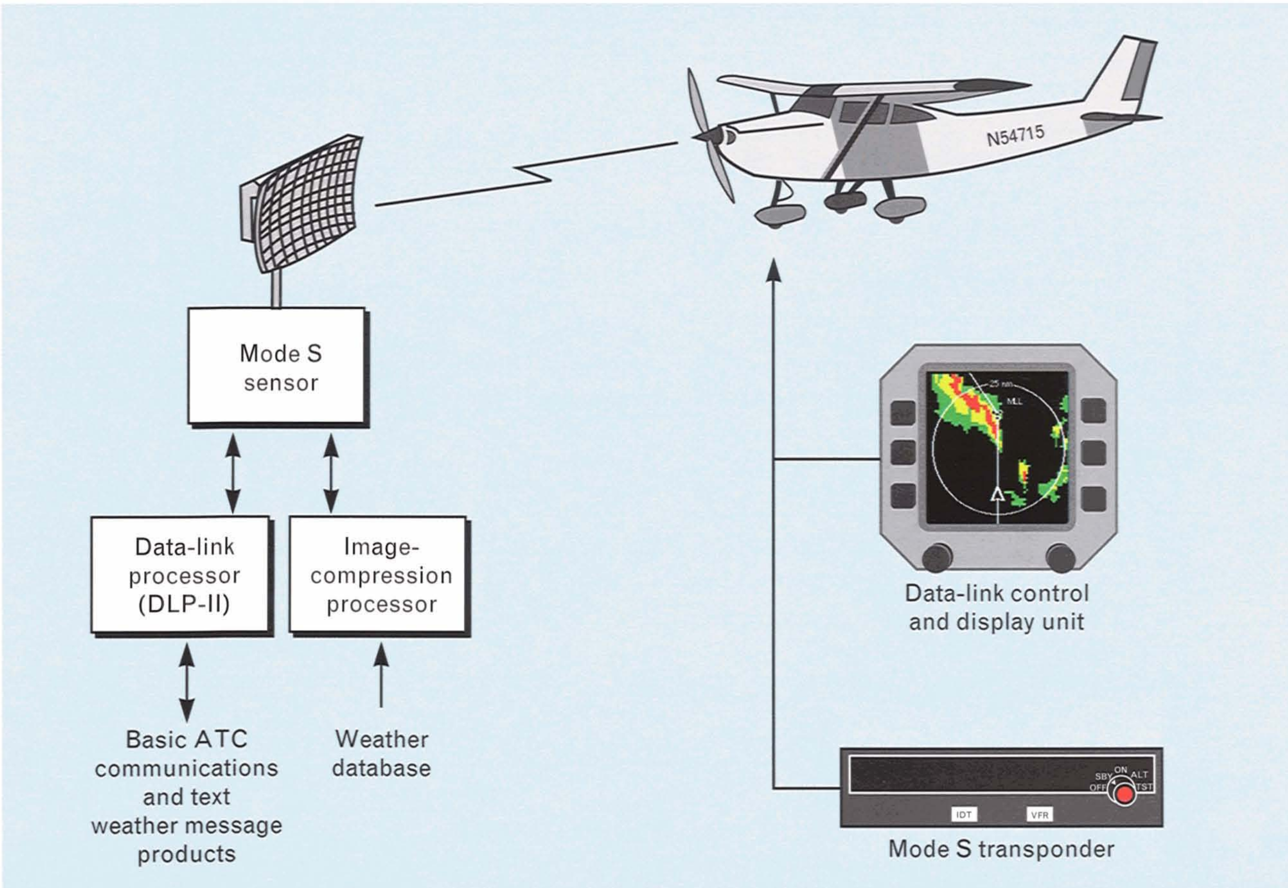

FIGURE 8. Graphical Weather Service (GWS). A real-time weather database is maintained in the image-compression processor connected to the data-link port of the Mode S sensor. Upon a request from an aircraft, the appropriate image is selected, compressed, and transmitted by data link to the aircraft, where the image is displayed.

Results of a recent human-factors study involving GA pilots indicate that GWS had a substantial positive effect on their weather-related decision-making process [9]. With the real-time graphical depiction of weather provided by GWS, pilots were able to make informed go/no-go decisions at the beginning of a simulated instrument flight. During these simulated flights, pilots were able to use the weather graphics to determine the need for course deviations without extensive use of verbal weather information provided by ATC controllers or Flight Service Station specialists. Pilots with extensive flight experience as well as those with limited experience benefited significantly from GWS.

Local Area Differential GNSS

The accuracy of the Global Navigation Satellite System (GNSS) is limited by systematic bias errors, beyond those introduced by the Department of Defense through the selective availability feature. To achieve sufficient accuracy to conduct precision instrument approaches with satellite navigation, estimates of these biases must be formed and corrections applied to the navigation solution. One method to provide these corrections is the use of a fixed ground station that uses its known position to formulate bias estimates and transmits these estimates to aircraft via data link. When implemented in a local area (roughly 20 nmi in radius), this technique is known as Local Area Differential GNSS (LADGNSS).

The choice of a data link to provide the LADGNSS corrections has been the subject of much study [10]. The FAA has recently determined that GNSS differential corrections and integrity information will be broadcast via satellite using the Wide Area Augmentation System (WAAS). The role of local-area differential corrections as backup to the WAAS or to support precision approach beyond Category 1 is yet to be determined. The issue centers on whether the data link is both available and protected from interference. The transmission of LADGNSS corrections has been demonstrated with the Mode S data link [11]. The corrections are broadcast in the local area surrounding an airport by the omnidirectional Mode S ground station described above (see Figure 9).

Aircraft with a data-link-capable Mode S transponder receive the corrections and pass them to the on-board GNSS navigation equipment, where the corrections are applied to the navigation solution. Appropriate navigation displays (e.g., emulation of localizer and glide-slope indicators) are then used to provide the pilot with guidance for the precision approach. Aircraft without Mode S transponders would be able to receive the corrections with a simple Mode S receiver designed to capture the LADGNSS broadcast. Such a low-cost receiver could be incorporated within the GNSS receiver itself to provide precision approach capability.

GPS-Squitter

In addition to the replies generated by ATCRBS and Mode S interrogations, the Mode S transponder produces a spontaneous reply called a *squitter* approximately once per second. This squitter, which is 56 bits in length, contains the unique Mode S address of the aircraft along with control and parity information. The squitter is designed to provide a TCAS-equipped aircraft with a means to acquire other Mode S aircraft in its vicinity without the need for acquisition interrogations. With a minor modification to the

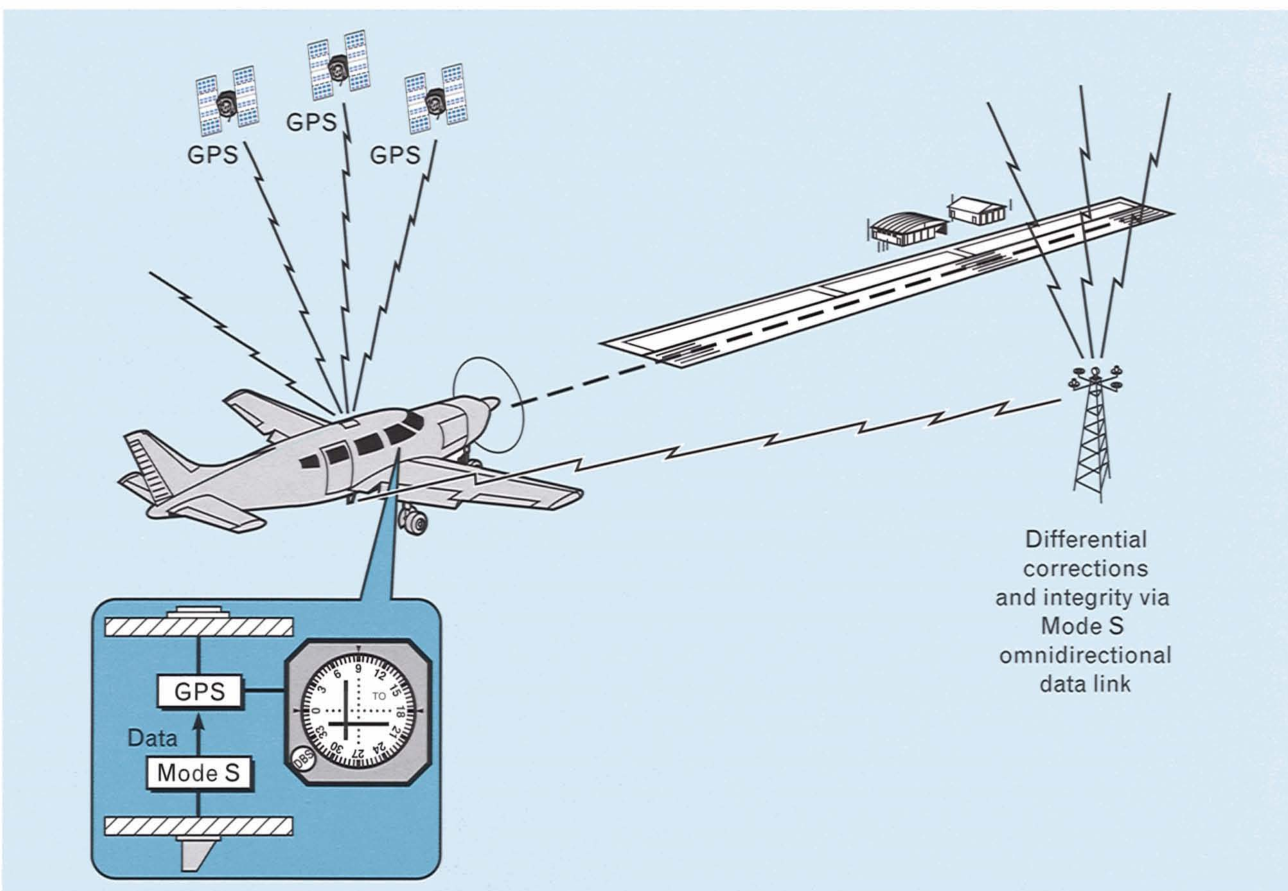

FIGURE 9. Local Area Differential GNSS (LADGNSS) precision instrument approach. An omnidirectional Mode S ground station is used to broadcast differential GNSS corrections to the area surrounding an airport. An aircraft with a Mode S transponder or a Mode S receiver applies the corrections to the GNSS navigation solution to achieve sufficient accuracy to perform a precision instrument approach.

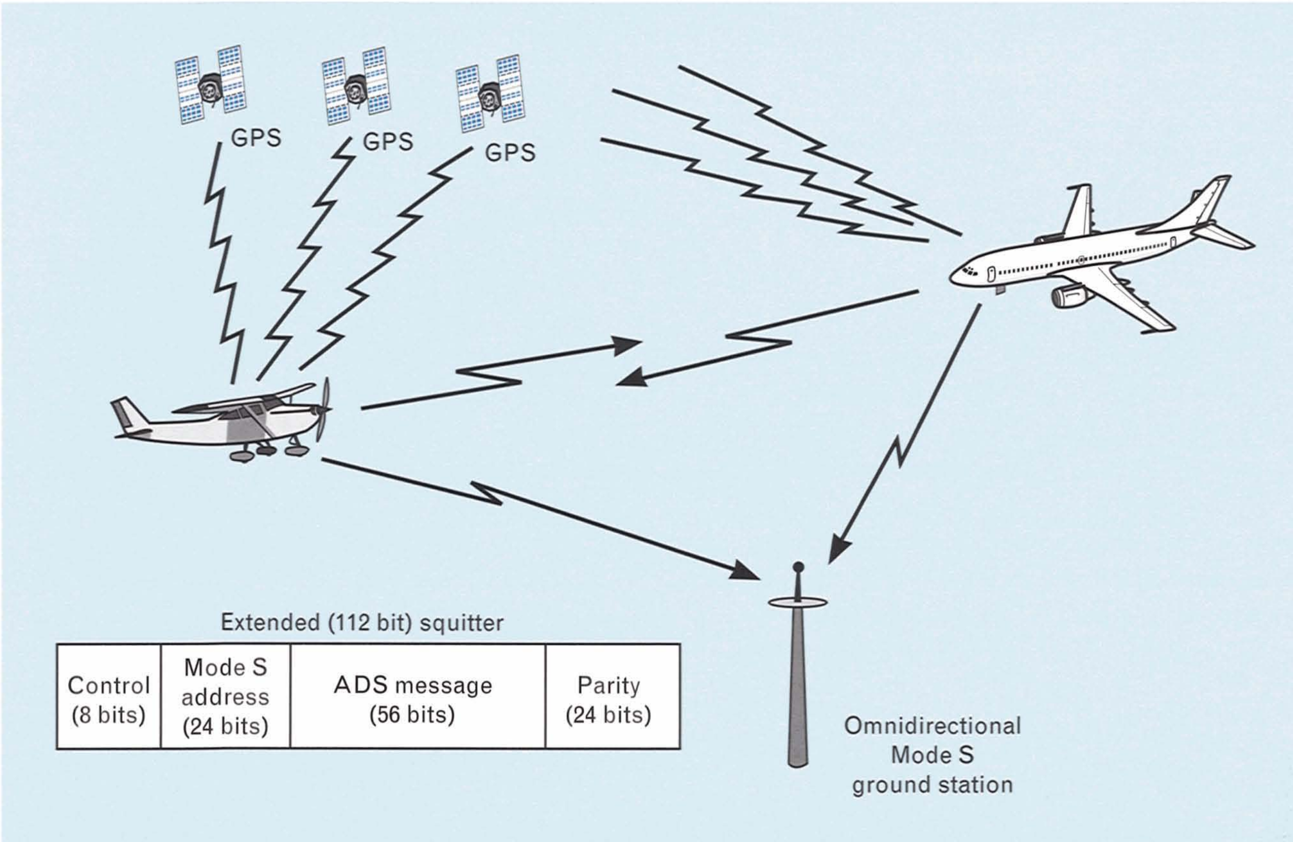

FIGURE 10. GPS-Squitter concept. Each aircraft derives its own position by using GPS satellite navigation and broadcasts an extended Mode S squitter containing that information. GPS-Squitters can be received by ground stations for ATC surveillance and by other aircraft for collision avoidance.

software within the Mode S transponder, another standard Mode S message, which is 112 bits in length, can also be squittered. The additional 56 bits in this extended squitter format are used by an aircraft to provide GNSS-derived position information, as shown in Figure 10. With this GPS-Squitter modification in place, an aircraft spontaneously broadcasts both its position and identification.

The omnidirectional Mode S ground station described earlier can monitor the GPS-Squitters broadcast by the aircraft in the vicinity. Such a ground station can then provide ATC with surveillance information as well as provide two-way Mode S data-link communications. These low-cost ground stations have been successfully demonstrated for both surface and airborne surveillance [5]. An aircraft equipped with a low-cost Mode S receiver can also monitor the positions of nearby aircraft by receiving their GPS-Squitters, decoding them, and presenting them on a cockpit display. This technique, called cockpit display of traffic information (CDTI), is likely to become the long-term solution to traffic situational awareness in the cockpit. Unlike TCAS and TIS, however, CDTI will require time to become effective because it relies on other aircraft to be equipped with GPS-Squitter so the aircraft can be "seen." Therefore, CDTI becomes effective only when a significant fraction of all aircraft (e.g., greater than approximately 80%) are equipped with GPS-Squitter.

A Typical GA Flight with Mode S Data Link

To illustrate the operation of Mode S data-link services, this section describes a hypothetical flight scenario for a typical GA aircraft. The flight originates at Hanscom Field in Bedford, Massachusetts, with a destination of Dulles International Airport in Virginia. Such a flight might take place in the spring of 1998, after deployment of DLP-II, GWS image-compression processors, and omnidirectional Mode S ground stations at satellite airports (including Hanscom Field). The aircraft is equipped with a Mode S data-link transponder and a CDU. The Mode S transponder is also connected to an aircraft GPS receiver and has been modified to produce GPS-Squitters.

After obtaining a detailed weather briefing by voice from a Flight Service Station briefer, or electronically with a personal computer and modem, the pilot files an Instrument Flight Rules flight plan from Hanscom Field to Dulles International Airport. The flight route will take the aircraft to the southwest across Long Island Sound, directly over Kennedy International Airport, then south along the New Jersey coast, west over the Chesapeake Bay to Baltimore, then directly to Dulles International Airport. The total flying time is estimated at three hours.

Start-Up and Taxi

Upon engine start-up at Hanscom Field, the pilot activates the aircraft's Mode S transponder and data-link CDU. The pilot makes a data-link request for Automatic Terminal Information System information and activation of his or her ATC clearance from a menu on the CDU. Because Hanscom Field is below the coverage of the Boston Mode S sensor, the data-link request sent by the Mode S transponder is received by an omnidirectional Mode S ground station located on top of the control tower at Hanscom Field. Within a second or two, the Automatic Terminal Information System message appears on the CDU display. An additional menu item on the CDU display indicates that the route clearance has been received from ATC; the pilot selects the route clearance for display and reviews it. Noting that ATC has modified the route slightly, the pilot acknowledges receipt and acceptance of the ATC clearance via data link.

Although full data-link communication with the Hanscom Field control tower is technically possible through the omnidirectional Mode S ground station, Hanscom Field does not support sufficient aircraft operations to justify the cost of the tower controller data-link communications consoles necessary to permit full ATC communications via data link. When the Hanscom Field control tower is not in operation, however (e.g., late at night), the omnidirectional Mode S ground station provides direct data-link communication with the Boston Terminal Radar Approach Control (TRACON) facility. This direct link permits the pilot to request and receive ATC clearance for departure when the local tower controllers are not available by voice radio. Because the Hanscom tower is in operation, the pilot relies on VHF voice-radio communication to obtain clearance to taxi to the active runway.

At the time the pilot received the preflight briefing, ground-based weather radar showed no precipitation on the route of flight. The current area forecasts, however, include the possibility of afternoon thundershowers over a large portion of western Connecticut, eastern New York, and New Jersey. To obtain an update on the weather situation prior to departure, the pilot manipulates the menu-driven display on the CDU to request a current weather-radar image of the subject area. The request is received by the omnidirectional Mode S ground station, and a compressed weather image is transmitted to the aircraft. This image, which is less than ten minutes old, shows some light-to-moderate shower activity over the Catskill mountains, but none along the route of flight. The pilot elects to depart and proceed on course, while monitoring the weather situation in-flight. The pilot obtains clearance for departure from the Hanscom control tower by VHF voice radio.

Departure and En Route

Once airborne, the pilot begins a climb to the ATC-assigned initial altitude of 2000 feet. Although the aircraft is still below the radar coverage of the Boston Mode S sensor, the GPS-Squitters that are spontaneously transmitted from the aircraft's Mode S transponder are received at the Hanscom Field omnidirectional Mode S ground station, and the surveillance information they contain is transmitted by land line to the Boston TRACON, where the symbol representing the aircraft appears on the display of the ATC controllers.

By selecting the appropriate menu on the data-link CDU, the pilot can perform all routine communications with ATC via Mode S data link. The pilot wishes to devote the data-link CDU display to traffic and weather information, however, and therefore elects to use VHF voice radio for ATC communication. In the event of a VHF voice-radio failure, the Mode S data link provides a backup means to communicate with ATC. From a menu on the CDU the pilot requests activation of TIS, and a traffic display appears as the aircraft enters coverage of the Boston Mode S sensor.

Once established at a cruising altitude of 8000 feet, the pilot requests an updated surface observation at Dulles International Airport and the latest weather radar image within a 100-nmi radius of Kennedy International Airport. As the aircraft proceeds southwest, it leaves the coverage of the Boston Mode S sensor and enters the coverage of the Mode S sensor located at Bradley International Airport in Windsor Locks, Connecticut. The transfer of surveillance and data-link coverage between Mode S sensors is performed automatically without any action required on the part of the pilot. During the remainder of the flight, the aircraft is constantly within the coverage of at least one Mode S sensor. The Bradley sensor automatically receives notification from the transponder that the pilot has requested TIS and maintains this service. Should the aircraft leave coverage of a Mode S sensor, and thus lose the ability to obtain TIS, the CDU display alerts the pilot that TIS is no longer available. Once the aircraft is across Long Island Sound, the transfer to the Mode S sensor at Islip, New York, takes place in a similar fashion.

Arrival

The latest weather-radar image received via data link indicates that the forecast thunderstorms are developing over the Catskill and Berkshire mountains and not in the New York City area, nor south along the route of flight. Therefore, the pilot elects to continue on the planned route. To monitor the situation more closely, the pilot selects a function from a menu on the CDU that automatically requests a weather-radar image update as soon as one becomes available (approximately every ten minutes). Approaching Baltimore, under the coverage of the Baltimore Mode S sensor, the pilot requests the Dulles Automatic Terminal Information System via data link and begins planning for the instrument approach to runway 1R. Although Dulles is equipped for full data-link communications with the ATC tower, the pilot elects to maintain VHF voice contact with ATC throughout the approach, landing, and taxi phases of the arrival.

Conclusion

The Mode S data link has the capability to provide the GA pilot with significant benefits in the form of improved situational awareness. The avionics required to obtain Mode S data-link services can meet the cost and size constraints imposed by the typical GA aircraft. Data-link applications such as Traffic Information Service and Graphical Weather Service can be provided with a relatively low investment in additional ground infrastructure. LADGNSS broadcast and GPS-Squitter can provide both ATC and the GA community with significant benefits in terms of improved surveillance and increased aircraft utility.

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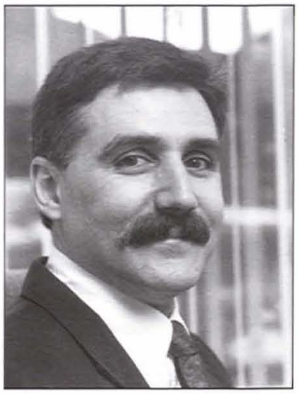

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