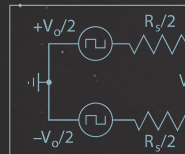
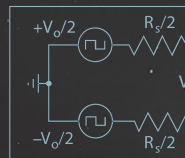
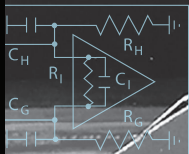
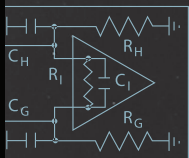




THIRD EDITION



DIGITAL AVIONICS HANDBOOK



EDITED BY

Cary R. Spitzer

Uma Ferrell • Thomas Ferrell



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EDITED BY

Cary R. Spitzer

In Memoriam

Uma Ferrell

Ferrell and Associates Consulting, Inc.

Thomas Ferrell

Ferrell and Associates Consulting, Inc.



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This book is dedicated in loving memory to Cary R. Spitzer.

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Preface

Avionics is the cornerstone of modern aircraft control and operation. Almost every facet of the aircraft is tied to one or more avionics functions. As a result, the complexity and cost of avionics have never been greater.

Many technologies that emerged in the last decade will be utilized in the next decade. The global positioning system has enabled satellite-based precise navigation and landing, and communication satellites are now capable of supporting aviation services. Thus, the aviation world is upgrading to satellite-based communications, navigation, and surveillance for air traffic management. Both the aircraft operator and the air traffic services provider are realizing significant benefits.

Familiar technologies in this book include data buses, one type of which has been in use for over 20 years; head-mounted displays; and fly-by-wire flight controls. New bus and display concepts, however, are emerging, for example, a retinal scanning display, which may soon replace these veteran devices.

Other emerging technologies include speech interaction with the aircraft and synthetic vision. Speech interaction may soon enter commercial service on business aircraft as another way to perform some noncritical functions. Synthetic vision offers enormous potential for both military and civil aircraft for operations under reduced visibility conditions or in cases where it is difficult to install sufficient windows in an aircraft.

This book offers a comprehensive view of avionics, from the technology and elements of a system to examples of modern systems flying on the latest military and civil aircraft. The chapters have been written with the reader in mind by working practitioners in the field. This book was prepared for the working engineer and others seeking information on various aspects of avionics. The topic of avionics cannot be fully explored in a single handbook. Readers are encouraged to make use of the References and Further Reading sections to explore topics in more detail.

The book has been divided into four sections, each containing a number of related chapters.

Section I deals with the evolution of air traffic control to air traffic management and the reason for avionics support in communication, navigation, and surveillance, as well as the supporting safety and certification infrastructure.

Section II deals with specific technology and use of different avionics, many of which are discussed in the previous section in a broad sense. Topics include an overview of functions accomplished by avionics, case studies of avionics architectures, and specific instances of avionics.

Section III is all about tools, techniques, and methods used to implement avionics functions. Topics include information on data buses, avionics architectures, modeling of avionics, and some additional details on navigation algorithms.

Section IV provides a long-range look ahead. While the industry is busy implementing NextGen, it is worth considering what a FarGen might look like.

Much of the information in this book deals with equipment and systems subject to regulatory oversight and certification. Certification and regulatory framework are constantly evolving as technology and the operating environment evolve (and yes, as lessons are learned from accidents and incidents). Opinions

expressed in these chapters are but one interpretation of standards used for compliance. The material presented here has been collected by the authors from many sources that are believed to be reliable. However, no expressed or implied warranty can be made as to the accuracy or completeness of the material. No responsibility or liability is assumed by the authors or their employers. While utmost care is taken to be aligned with the certification authority, the final acceptance of that interpretation within a specific context is up to the certification authority. Many of the standards discussed in this book are coupled with issue papers or certification review items to augment their application on specific projects. For these reasons, it remains the responsibility of the entity seeking approval of their avionics for flight to demonstrate compliance to all necessary regulatory requirements.

Avionics concepts are developed and regulated world-wide using numerous industry documents from organizations such as RTCA, European Organization for Civil Aviation Equipment (EUROCAE), Society of Automotive Engineers (SAE), etc. These documents are developed in committees comprised of industry, academia, and regulators. There are also numerous regulatory documents that affect how avionics are developed, used, and maintained. Naturally, a number of these documents have been referenced, elaborated, and made use of to describe concepts within many chapters in this handbook. The chapters in this handbook are not meant to substitute these industry documents or regulatory documents that promulgate the rules. Furthermore, all of these documents evolve from time to time. It must be noted that applicable regulations take precedence over materials in this handbook. Applicable industry documents must be directly referenced for application on specific projects since it is quite conceivable that a specific version of a specific industry document may be imposed in the regulation applicable to that project.

Acknowledgments

Heartfelt thanks to Tom and Uma Ferrell—your dedicated work made this book a reality. Because of his illness, Cary struggled and was unable to complete this project. He would be grateful and pleased. Thank you, Nora, for keeping me informed of the progress of this book.

Laura Spitzer

We would like to thank all of the contributing authors of this handbook. Without their dedication, this book would not have been possible. We also would like to thank Taylor & Francis for seeing this project to conclusion. Finally, the resulting volume would not have been possible without the diligence and hard work of Nora Konopka and Deepa Kalaichelvan. Thank you very much.

Tom and Uma Ferrell

Editors

Cary R. Spitzer (deceased) graduated from Virginia Tech and George Washington University. After service in the Air Force, he joined NASA Langley Research Center. During the last half of his tenure at NASA, he focused on avionics. He was the NASA manager of a joint NASA/Honeywell program that made the first satellite-guided automatic landing of a passenger transport aircraft in November 1990. In recognition of this accomplishment, he was nominated jointly by ARINC, ALPA, AOPA, ATA, NBAA, and RTCA for the 1991 Collier Trophy “for his pioneering work in proving the concept of GPS-aided precision approaches.” Mr. Spitzer led a project to define the experimental and operational requirements for a transport aircraft suitable for conducting flight experiments and to acquire such an aircraft. Today, that aircraft is the NASA Langley B-757 ARIES flight research platform. Mr. Spitzer was the NASA representative to the Airlines Electronic Engineering Committee. In 1988, he received the Airlines Avionics Institute Chairman’s Special Volare Award. He was only the second federal government employee so honored in over 30 years. He was active in the RTCA, including serving as chairman of the Airport Surface Operations Subgroup of Task Force 1 on Global Navigation Satellite System Transition and Implementation Strategy and as technical program chairman of the 1992 Technical Symposium. He was also a member of the Technical Management Committee. In 1993, Mr. Spitzer founded AvioniCon, an international avionics consulting firm that specializes in strategic planning, business development, technology analysis, and in-house training.

Mr. Spitzer was a fellow of the Institute of Electrical and Electronics Engineers (IEEE) and an associate fellow of the American Institute of Aeronautics and Astronautics (AIAA). He received the AIAA 1994 Digital Avionics Award and the IEEE Centennial Medal and Millennium Medal. He was a past president of the IEEE Aerospace and Electronic Systems Society. Beginning in 1979, Mr. Spitzer played a major role in the highly successful Digital Avionics Systems Conferences, including serving as general chairman. Mr. Spitzer presented one-week courses on digital avionics systems and on satellite-based communication, navigation, and surveillance for air traffic management at the UCLA Extension Division.

He also lectured for the International Air Transport Association. He was the author of *Digital Avionics Systems*, the first book in the field, published by McGraw-Hill, and editor-in-chief of *The Avionics Handbook*, published by CRC Press.

He held two patents, published more than 40 papers, and was the author of several books on avionics. Having written a tutorial on avionics, he was sought after as a consultant by UCLA and lectured all over the world. He was proud of the fact that his book, *Digital Avionics Systems*, was translated into Chinese and widely distributed in the Orient.

Uma Ferrell and Thomas Ferrell are cofounders of Ferrell and Associates Consulting, Inc. (FAA), a certification and software safety consultancy serving the aerospace industry. They have over 50 years of combined experience in helping industry in accomplishing certification objectives via training, certification project support, and related research. They are frequently sought out to help with new and novel technologies and methods where traditional certification approaches break down. In recent years,

their consultancy has evolved to include project management support, especially for projects in need of recovery plans, to ensure successful engine and airframe certification. Mr. and Mrs. Ferrell have collaborated together in numerous industry efforts as well as jointly authored papers and tutorials for a number of industry conferences, most notably the Digital Avionics Systems Conference (DASC) and the International System Safety Conference (ISSC). They authored the FAA's *Service History Handbook* (DOT/FAA/AR-01/116), an alternative method for DO-178B compliance. Their other research efforts have included work on the use of wireless systems onboard aircraft (accomplished through AVSI) and a comprehensive review of existing airworthiness standards for use in commercial space conducted for the FAA. Mr. and Mrs. Ferrell have authored and presented numerous courses covering various aviation engineering topics, including DO-178C, DO-178B, DO-254, DO-200A, DO-201A, FAA aircraft certification, system and software safety, engineering ethics, technology transfer, and software verification for aviation systems.

Uma Ferrell holds a master's degree in electrical engineering from Johns Hopkins University. She also holds an MSc in solid-state physics; a BSc in physics, chemistry, and mathematics; and a BSc (honors) in physics from Bangalore University in India. Mrs. Ferrell has held senior technical positions at Reliable Software Technologies (RST), The MITRE Corporation, General Sciences Corporation (GSC), and Computer Sciences Corporation (CSC). She has also contributed to engineering of large-scale, mission-critical scientific information systems for National Aeronautics and Space Administration (NASA), National Oceanic and Atmospheric Administration (NOAA), and the Federal Aviation Administration (FAA).

Mrs. Ferrell has participated in a number of industry standards efforts, including work for both the RTCA and the IEEE. She served as the U.S. cochair of the Commercial Off the Shelf Software (COTS) subgroup of RTCA SC-190 for CNS/ATM-related ground systems. She has conducted numerous engineering studies for the requirements working group of RTCA SC-147 (traffic alert and collision avoidance system (TCAS) Minimum Operational Performance Specification). She represented The MITRE Corporation at the RTCA Certification Task Force to provide policy recommendations to the FAA. She was a part of RTCA SC-200 to establish design guidance and certification considerations for integrated modular avionics in RTCA DO-297. She has also contributed to RTCA SC-205 for the formulation of DO-178C, DO-248C, and DO-278A for CNS/ATM systems.

Mrs. Ferrell is a software designated engineering representative (DER) (parts 23 and 25) Level A for both electrical and mechanical systems. She also performs similar work as an authorized representative (AR) for numerous FAA ODAs. She currently serves on the ASQ *Software Quality Professional* editorial board, providing jury review of software-related publications.

Mr. Thomas Ferrell holds a bachelor's degree in electrical engineering from Northern Illinois University, a master's degree in information technology management from Rensselaer Polytechnic Institute, and, for something a little different, a master's degree in history from George Mason University. Mr. Ferrell has held senior technical positions at Science Application International Corporation (SAIC), Iridium LLC, and the Boeing Commercial Airplane Group.

Mr. Ferrell has served in various leadership capacities for a number of RTCA committees, including SC-190, where he led the effort to create DO-278, and SC-205, where he was responsible for DO-178C document integration. He has served as a private sector advisor to the FAA at ICAO. He is frequently sought out as a guest speaker on a variety of topics associated with system and software safety, as well as aircraft certification.

Mr. Ferrell is a software and airborne electronic hardware designated engineering representative (parts 23, 25, and 33) for electrical and mechanical systems, as well as engine controls. He is also an authorized representative (AR) for numerous FAA ODAs.

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The first section deals with the evolution of air traffic control (ATC) to air traffic management (ATM) and the reason for avionics support in communication, navigation, and surveillance and the supporting safety and certification infrastructure. The chapter on NextGen/Single European Sky ATM Research (SESAR) gives a broad description of the context in which aircraft operates; while pilots retain tactical control, ATM retains the strategic control in order to promote safety and efficiency. The different chapters in this section deal mostly with the avionics portion of the functions even though none of these functions are complete without considering the ground portion also. While the chapter on communication is a broad brush on the historic narration as well as various developments in technology, the chapter on navigation is more focused on algorithms. The surveillance part of the communications, navigation, and surveillance (CNS) is dealt with in the chapters on global positioning system (GPS), automatic dependent surveillance-broadcast (ADS-B), and TCAS II. The next group of chapters deals with the basic equipment that allows the aircraft to be managed within the airspace. Safety-specific avionics are discussed in the next group of chapters. Finally, the set of certification-specific guidance that supports design and development assurance are discussed.

Evolving Avionics: Meeting the Challenge of NextGen and SESAR

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1.1 Avionics: A Historical Perspective

1.1.1 Term

The term avionics was coined from “aviation” and “electronics” in the 1970s. If we broaden the definition to include instruments and mechanical systems, many systems such as radios, altimeters, radar, fuel gauges, and navigation instruments were used in the cockpit before the advent of electronics driven by the military.

1.1.2 Technology, Safety, and Regulations

Ever since the advent of powered flight in 1903, aviation has continuously progressed with a variety of advances in all fields, science and engineering of flight as well as how to control the skies for safety from collisions with other aircraft, terrain avoidance, weather avoidance, and safe landing and takeoff.

Industry leaders pushed to have common safety standards imposed by a government agency—the resulting Air Commerce Act in 1926 was the beginning of the federal certification authority in the United States. ATC centers were established in Newark, Cleveland, and Chicago to help pilots with en route directions. Traffic was controlled using blackboards and “shrimp boats” (paper boats signifying the airplane position) that were manually progressed depending upon the information from dispatchers, radio operators, and airports via telephone. In the history of the Federal Aviation Administration (FAA), two separate branches were created via Civil Aeronautics Act of 1938—one with the responsibility for Air Traffic Control (ATC) and another with the responsibility for safety rulemaking, accident investigation, and economic regulation of airlines. The early ATC based on visual signals and light beacons evolved to radar signals following World War II technical developments. The advent of jets and higher density of traffic provided more challenges for safety. Avoidance of midair collisions, terrain, and weather came to sharp focus with

each high-profile accident. A single department of transportation to cover all modes of transportation including air transportation was established in 1986 via congressional authorization for a cabinet department with a separate authority for accident investigation transferred to the National Transportation Safety Board. This act took the agency to become the Federal Aviation Administration that we have today. A number of rules and regulations have evolved with both the evolution of technology and the recognition of the need for new technology instigated by accidents, incidents, increase in traffic, and increase in operating costs.

1.1.3 Top Three Technologies and Air Traffic Control

The three essential technologies available to pilots in air and air traffic controllers on the ground that help tactical and strategic control of aircraft with coordinated functions are communications, navigation, and surveillance. The challenges of these systems include global compatibility and interoperability as well as affording the service to both military and civil aircraft.

The three aspects of avionics, namely, Communications, Navigation and Surveillance (CNS), have a parallel history in that advancements in one area necessitate advances in other areas. Wartime advances in navigation and radar detection required that communications be made more sophisticated. These advances were brought into civil aviation; the same radar technology that was used in military aviation was adapted to be used to control civil aviation. Increase in the air traffic necessitated more dependency on distributed CNS equipment both on ground and air to orchestrate traffic efficiently while avoiding conflicts. To address the high price of oil during the 1970s, more and more digital systems were introduced to more precisely control flight. As more and more instruments were introduced into the cockpit, some aids such as autopilots and warning systems had to be introduced to address pilot workload.

Navigation in general is determining own position and velocity so that position and velocity at a future time can be calculated with and without changes in velocity. Navigation of aircraft from a pilot point of view is to know where the aircraft is with respect to a planned track so that the aircraft motion can be controlled. Navigation consists of four functions, namely, planning, tracking, recording, and controlling the aircraft motion. Air navigation has evolved from early ship navigation. In the early days of air travel, avionics equipment for navigation was as rudimentary as following known landmarks such as rail tracks or rivers combined sometimes with sophisticated celestial navigation techniques until there was a need to fly in conditions where visibility was poor because of night flying or bad weather conditions. The basic idea of accurately locating own ship was increasingly important as the skies became crowded and they had to be strategically organized to fly specific routes via a centralized ground control. The first blind flight and landing based on navigation using gyroscopes and radio navigation aids was at the end of the 1920s. Today, aircraft could be flown under visual flight rules (VFR) or instrument flight rules (IFR). Accurate navigation technology has been used to maximize the airspace capacity while balancing safety. Navigation systems must satisfy four important categories of performance requirements, namely, accuracy, integrity, availability, and continuity of service.

The third aspect of surveillance is determination of the position and velocity of the aircraft as perceived from the outside of the aircraft (e.g., from the ground ATC). Most of the improvements in the CNS were a direct result of technologies developed during World War II. Radio beacons and directional beams came to being in the 1930s. The first ATC tower was established in 1935 at the Newark Liberty International Airport in NJ in 1935. There are two types of radar onboard the aircraft: primary surveillance radar and secondary surveillance radar. The primary surveillance radar is passive in that the ground detects the radar energy scattered from the surface of the aircraft to measure the distance and heading of the aircraft relative to the source of radar on the ground. The secondary surveillance radar is active in that the radar from the ground initiates a transponder on the aircraft that transmits a reply to the ground signal. This type of transmission can also be picked up by the surrounding aircraft to aid in collision avoidance. A unique address is given to each aircraft so that its transponder transmissions can be unambiguously identified. This addressing system is followed throughout the world so that the aircraft transponder is useful

in all airspace. Transponder signals, whether from primary surveillance radar or secondary surveillance radar, will be displayed on the ATC console. Radar signals have been extended to aid in detecting weather and terrain. Navigation and surveillance ideas have been combined using technology such as Automatic Dependent Surveillance-Broadcast (ADS-B) to accomplish avionics for collision avoidance for manned as well as unmanned systems, terrain avoidance, terminal aviation hazard detection, and assistance in using parallel runways. These are only some examples of the ever-growing suite of avionics.

ATC has evolved into ATM, which is using processes, procedures, and resources to assure that aircraft are guided in the sky and on the ground. Aircraft safety is a responsibility shared and divided between the ground and the air. Since these responsibilities are so interconnected, the concepts of Required Communications Performance (RCP), Required Navigation Performance (RNP), and Required Surveillance Performance (RSP) have been introduced to support efficient separation between aircraft while addressing possible constraints of the equipment and related procedures. Thus, many of the avionics that are described in this handbook ultimately support the strategic management of aircraft in giving proper tools to the pilot.

1.2 Free Flight to NextGen/SESAR

The earliest ATC guiding multiple aircraft was in the early 1930s when the controllers tracked the position of planes using maps, blackboards, and “shrimp boats” with only telephone connections to airline dispatchers, radio operators, and other airport air traffic controllers. The same basic system continued as improvements were made to communications, radar sensor data, electronic displays, etc. Many discrete automation systems were introduced in different air traffic facilities as these were helping the ever-evolving complexity and decision making of the air traffic controllers. These systems introduced complexity in configuration management of existing functionality and any new introduction of functionality for interoperability. National Airspace System (NAS) plan was introduced by the FAA to systematically manage projected growth for air travel over the next 20 years. This plan proved to be too ambitious; a new Free Flight program was introduced to take advantage of newly developed GPS technology. This concept took NAS from a centralized command-and-control system between pilots and air traffic controllers to a distributed system that allows pilots, whenever practical, to choose their own route and file a flight plan that follows the most efficient and economical route. This concept made way to a distributed ATM, which combined distributed decision making for traffic separation and self-optimization. These traits demand that the aircraft have specific capabilities measured as required performance in CNS. The resulting concept is known as performance-based navigation, which is one of the primary concepts of NextGen and SESAR. In other words, NextGen and SESAR are programs that implement technology that will allow Free Flight concepts to be used safely and securely in an environmentally responsible manner; the concepts include transformation of the air transportation system by changing technologies, infrastructure, and procedures. The resulting demands on avionics suite to be used by aircraft are RCP, RSP, and RNP.

RCP defines the required performance of each element of the communications network, including the human element. Each element must perform with certain specifications in order to maintain defined aircraft separation standards. RCP has specific time requirement in seconds for messages sent and then received. The complete end-to-end communication limit is either 240 or 400 s based on aircraft equipment and the ability to have an alternate means of establishing communication if the primary fails.

RSP defines system technical performance requirements independent of technology and architecture to be met by an air traffic service (ATS) surveillance system in order to support a particular ATS service or function. Similar to RCP, RSP also has specific performance requirements in seconds for messages sent and received. The completed end-to-end communication cycle is either 180 or 400 s based on aircraft equipment and whether there is an alternate means of establishing communication if the primary fails.

RNP is “a statement of the navigation performance accuracy necessary for operation within a defined airspace.” There are two values that express this qualification—a distance in nautical miles called

“RNP type” and a probability measure that is 95% for 1 X RNP and 99.999% within 2 X RNP. For example, an airplane is qualified to operate in an RNP 4 airway; the aircraft must have a demonstrated capability of its navigation system to result in the airplane being within 4 nmi of the indicated position on the navigation system at least 95% of the flight duration within a given flight segment or phase. It is also necessary for the navigation system to issue a warning to the pilot when this condition cannot be met. Within the “containment limit” of twice the RNP, in this example, 8 nmi of the indicated position, the indicated position on the navigation display panel which includes the total system error is expected to not exceed the designated RNP number at least 99.999% of the flight duration within the same segment or phase.

Required total system performance (RTSP) is a combination of RNP, RSP, and RCP as well as ATC surveillance capability, which defines a benchmark for separation minima and collision safety risk. The required performances are operationally derived without any dependency on any specific techniques, technologies, and/or architecture.

Evolution in ATM impacts airborne avionics equipment, flight planning, airspace planning, ground infrastructure, procedures used for managing flight traffic, certification, and related activities and stakeholders. This evolution can be viewed by many of these perspectives; indeed there have been many industry activities that have contributed to this evolution.

1.3 NextGen

GPS technology has given pilots the tools needed for planning point-to-point flights rather than planning via way points. This satellite-based system will allow for shorter routes, savings in time and fuel, reduction of delays, and increase in en route capacity by giving pilots the tools to fly closer together on direct routes. Better communication between pilots and ground controllers will accommodate an efficient use of airports. Data fusion is being planned to collect global weather observations into a common weather picture

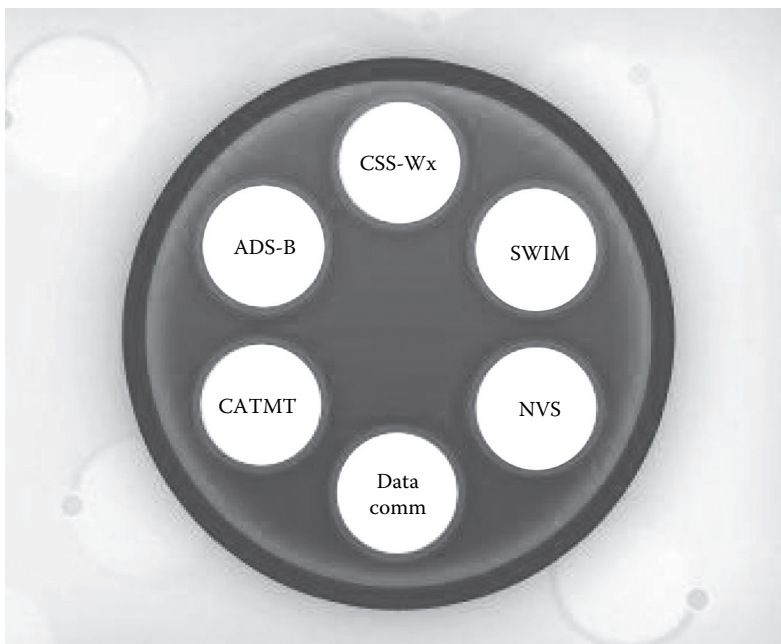


FIGURE 1.1 Core set of tools for NextGen. (Courtesy of Federal Aviation Administration, Washington, DC, Available online at: https://www.faa.gov/about/office_org/field_offices/fsdo/orl/local_more/media/fy13summit/NEXTGEN_MCO_Safety_Summit.pdf, accessed on April 27, 2014.)

to enable better tactical and strategic traffic management decisions. These various goals are being accomplished by a core set of tools shown in Figure 1.1: NAS Voice System (NVS) accommodates the key voice communication component of NextGen, System-Wide Information Management (SWIM) allows sharing of information, Common Support Services Wx (CSS-Wx) is used for disseminating weather information via SWIM, Collaborative Air Traffic Management Technologies (CATMT) provides enhancements to existing traffic flow management systems and works with SWIM, ERAM processes flight radar data and provides real-time aeronautical information, and ADS-B increases situational awareness. While some of the following goals are still experimental, some have already been realized in the field as published/updated by the FAA:

1. Use of GPS and ADS-B to create a single real-time display of air traffic that has the same information disseminated to both pilots and air traffic controllers. The use of satellite-based precision approach procedures can be done even in low visibility, without needing ground-based landing systems; many small airports may have only one or no instrument landing system.
2. Creation and provision of a common weather picture across the national airspace. Many different tools provide icing and turbulence information at different altitudes to pilots.
3. Greater use of data communications via data link for routine messages between pilots and controllers.
4. Use of a single voice communication system for air/ground and ground/ground communications.
5. Integration of unmanned aircraft system into the airspace

NextGen utilities and concepts are being put into place in a number of airports with decidedly positive results.

SWIM is the key tool that is used in common with international systems to make NextGen compatible with SESAR. SWIM is used for collecting and sharing system-wide information of aircraft and ground facilities. SWIM services handle five data domains, namely, flight data, aeronautical data, weather data, surveillance data, and capacity and demand data. SWIM was adopted by ICAO in 2005. This service-oriented architecture uses existing networks, off-the-shelf hardware, and SWIM-compatible software tools to provide sharing of near real-time information by airline operations, air traffic managers and controllers, and the military (Figure 1.2).

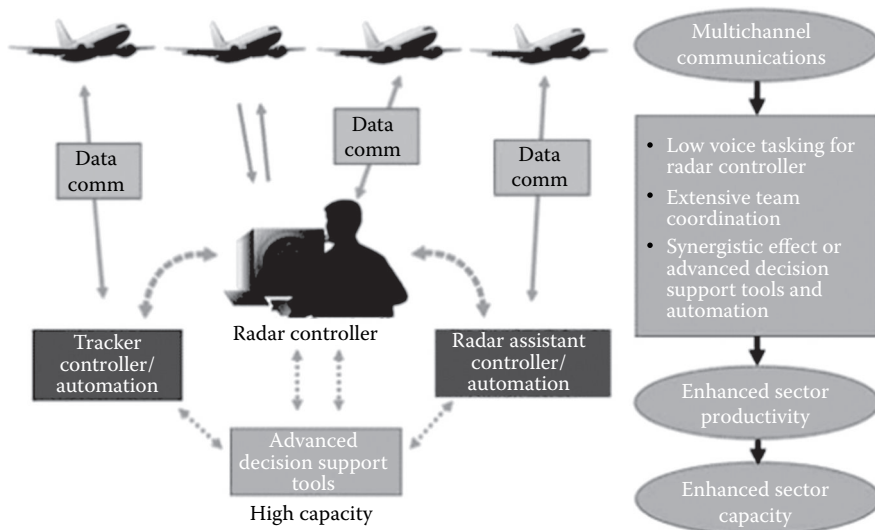


FIGURE 1.2 (See color insert.) Tomorrow: Evolved sector with data comm. (Courtesy of Federal Aviation Administration, Washington, DC, Available online at: https://www.faa.gov/about/office_org/field_offices/fso/orl/local_more/media/fy13summit/NEXTGEN_MCO_Safety_Summit.pdf, accessed on April 27, 2014.)

1.4 SESAR

Since Europe is made up of different countries, there is no single management of air navigation services. ATC over Europe is extremely busy and dense. These factors make for a very complex system. The initiative of Single European Sky was introduced to provide a uniform level of safety and efficiency for all of Europe by reorganizing and restructuring European airspace without being constrained to national borders. SESAR is a joint undertaking among all of the stakeholders to define, develop, and deploy a high-performance ATC infrastructure. Converting from airspace-based management to trajectory-based operations and employing an integrated data communication system are the important features of SESAR, just as NextGen. A set of key performance areas has been defined to focus and measure the progress. These performance areas are interdependent but have to be balanced in making trade-off decisions. The performance areas focus on accommodating increase in traffic in a safe and efficient manner with environmentally friendly methods. SESAR trials have proven success in select airports.

1.5 Summary

For both concepts, NEXTGEN and SESAR, the operations are based on shared net-centric information to aid collaborative decision making by all stakeholders and trajectory-based operations for efficient use of resources in both air and ground. There are differences between the two systems in the way the data are compiled and distributed; while NextGen is more centralized, SESAR is distributed. NextGen is mainly government controlled to ensure interoperability of components, while SESAR is a single multi-stakeholder consortium. Both NextGen and SESAR represent enormous challenges since the change is one of a paradigm shift and adaptation to new technology. European and American authorities have an agreement on interoperability between their respective ATM infrastructures, thus allowing for uniformity in required avionics capabilities as well.

Further Reading

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Communications

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2.1 Air–Ground Communications

2.1.1 History

Airplanes became a tool of war in World War I; they became a tool of commerce in the following decade, the Roaring Twenties. In Europe and America, aircraft were used for entertainment and later as a means to carry mail from city to city. As the number of airspace users grew, so did the need for communications between companies and their pilots, as well as between pilots and the nascent air traffic control (ATC) (namely, airports). Early attempts at air–ground communication used visual means: lights, flags, and even bonfires. But more was needed. Early radios used Morse code to communicate, but that was not practical in an open, bouncing cockpit. With practical voice radios, air–ground communications became a necessary element of the fledgling air transport industry, and it remains so to this day.

In the 1970s, the airlines introduced data communications to aircraft in flight for company communications using the Aircraft Communications Addressing and Recording System (ACARS). Various trials by air navigation service providers (ANSPs) have proven the effectiveness of data communications for ATC. Some oceanic and remote areas have implemented ATC operations via data link, and trials in domestic airspace have shown the value of this medium.

In the 1990s, the International Civil Aviation Organization (ICAO) developed the *Manual for the Aeronautical Telecommunication Network (ATN)*, which specified an air–ground data network based on the International Organization for Standardization (ISO) Open Systems Interconnection (OSI) model. Subsequent work extended this network to support the Internet protocol suite (IPS).

2.1.2 Introduction of Radios

Early on, the use of radio waves was recognized as an important resource. By its third decade, national and international bodies were allocating the radio spectrum. In the United States, the Federal Radio Commission (FRC), predecessor to the Federal Communications Commission (FCC), was licensing radio frequencies to operators. In 1929, the FRC directed the aircraft operating companies to band together to make consolidated

frequency allocation requests. Aeronautical Radio Inc. (ARINC) was formed in that year specifically for that purpose. The department of ARINC which was responsible for aeronautical radio frequency allocation in the United States is now an independent company known as Aviation Spectrum Resources, Inc. (ASRI). To resolve any issues in the aviation spectrum associated with the use of voice and data at the national and international levels—FAA and FCC work in cooperation and negotiate at the ICAO level.

As would be expected, communications needs were greatest around airports. Since each aircraft operating company had its own frequency allocation and its own radio operators, as the industry grew, the need for more frequencies grew. This recurring problem, known as spectrum depletion, has been solved in various ways. In the early days, it was solved by banding together to use common frequencies and radio operators. ARINC was a natural choice to implement these common radio stations. At one point, ARINC had 55 such communication centers across the United States.

Another method of solving spectrum depletion was the introduction of new technology. The steady improvements in radio technology have opened higher and higher frequency bands to practical communications use, subject to physical limitations. The increased sophistication of radio circuitry allowed different ways of modulating (i.e., impressing information onto) the radio signals. Initially, these improvements allowed better, clearer, and more efficient and effective voice communications. Later technology permitted the evolution of data communications.

The combination of higher usable frequencies and improved modulation techniques has served to extend the useful life of air-ground voice communications for nearly a century. In the 1930s and 1940s, air-ground voice moved from the high-frequency (HF) to the very-high-frequency (VHF) bands. Amplitude modulation (AM) was used and continues to be used as the basic means of ATC communications in domestic airspace. Long-range voice communications relies on the properties of the HF band, as will be discussed later.

2.1.3 Introduction of Data Communications

As the airlines came to rely increasingly on information provided to and received from the aircraft in flight, voice gave way to data. Changeover from voice to data has a number of reasons such as different pilots and different air traffic controllers with various accents (even though canned words were used), clarity in transmissions, distortion, and overlap between different conversations. Data transmission is cleaner and less intrusive. Automating responses where they can be automated also improves efficiency for both the air traffic controllers and the flight crew. In 1978, the airlines initiated air-ground VHF data link, which served two purposes: (1) to allow the messages to originate automatically on the aircraft, reducing crew workload, and (2) to allow the messages to be relayed to airline computer systems without any ground radio operators. The data link was initially called the ARINC Communications Addressing and Reporting System (ACARS), but “ARINC” was soon changed to “Aircraft” in recognition of the nonproprietary nature of the new medium.

Air-ground data link has become the mainstay of airline operations. In the early days, ACARS messages consisted primarily of four automated downlinks per flight segment: the so-called OOOI (pronounced oo-ee) or Out, Off, On, and In messages. These messages allowed the airlines to better track their flights and provided automated timekeeping on the crew. The original 50 aircraft participating in ACARS have grown to almost 10,000. The number of messages now tops 20 million in a month, and the types of messages cover every imaginable facet of airline operations: flight operations, administrative information such as crew scheduling, passenger information such as connecting gates, maintenance information such as engine performance and failure reports, airport and airline coordination such as deicing and refueling, and so on. Also, now many data link transactions are two way, including uplinks as well as downlinks. In fact, some applications are interactive with requests and responses initiated by the ground or by the flight crew. Although these interactive transactions via data link lack the immediacy of voice conversations, they are asynchronous in that both requestor and responder need not be “on the line” at the same time. For non-time-critical applications, this is a significant advantage.

2.1.4 Introduction of ATC Data Link

While VHF voice remains the primary means of ATC communications in domestic airspace, ACARS was first approved for ATC in the South Pacific flight information regions (FIRs) in 1995. Initially, Boeing 747-400 aircraft flying between the United States west coast and Australia and New Zealand pioneered ATC data link by using controller–pilot data link communications (CPDLC) and automatic dependent surveillance (ADS). Boeing offered this combination of features in the Future Air Navigation System (FANS)-1 avionics package. FANS—originally an acronym coined by the ICAO—was a term covering communication and navigation using satellites; however, the term has taken on a life of its own. Airbus released a similar capability package and named it “FANS-A.” So, FANS-1/A, as it is now known to acknowledge both packages of the same ADS and CPDLC applications, is being supported by air traffic service providers all over the world. The original air traffic service providers of the South Pacific have been joined by those of the North Atlantic, North Pacific, Indian Ocean, far east Russia, China, South Africa, and other regions.

Prior to the use of ACARS for airborne ATC communications, two applications were implemented on the ground between the aircraft and ATC: Pre-Departure Clearance (PDC) and Digital Automatic Terminal Information Service (D-ATIS). The receipt and acknowledgment of these messages by the flight crew is mandatory prior to takeoff and landing. Receiving these messages via ACARS has several significant advantages. For the flight crew, the message need not be transcribed for later reference, and it can be requested and received without the effort of finding the proper voice channel and requesting the PDC or listening for the beginning of the recorded ATIS. The tower controller need not line up all of the PDC slips, call each aircraft, read the clearance, and verify the readback. Plus the reduction in congestion on the clearance delivery channel is a significant advantage for situations such as peak departure times at a busy airport.

All of these ATC applications use the ACARS air–ground link, which was neither designed for nor initially approved as an ATC communication medium. For that purpose, ICAO developed standards and recommended practices (SARPs) for the Aeronautical Telecommunication Network (ATN), which was designed for both air–ground and ground–ground communication. In the latter role, it is intended to replace the Aeronautical Fixed Telecommunication Network (AFTN), which has served the industry well as a teletype-based, message-switching network for many years. However, technology has overtaken AFTN, and the more modern packet-switched technology of the ATN is seen as more appropriate. The ATN SARPs’ development began in the early 1990s. In the past 15 years, the Internet, which is based on a different packet-switched technology, that is, Transmission Control Protocol/Internet Protocol (TCP/IP), has had unprecedented success. ICAO has created another set of ATN SARPs to accommodate the IPS, known as the ATN/IP SARPs. The original ATN, based on OSI protocols, is now known as the ATN/OSI.

As ACARS became essential to airline operations, the limitations of the initial VHF link became intolerable, first because of coverage limitations and then because of speed. The former was solved in two different ways. Long-range data link was implemented first using Inmarsat satellites; this was the basis for initial FANS implementations in the South Pacific. The oceanic coverage, direct pilot-to-controller communication, and improved performance provided by satellites and data link were an improvement over HF voice services. All of the advantages of data link over voice communications were highlighted in the initial FANS trials and operational use. The advantages included (1) direct controller–pilot communications; (2) consistent and rapid delivery of messages; (3) standardized message texts, which were understood by all no matter what their native language is; (4) automated delivery of position reports; and (5) integration of message content with flight management systems (FMSs). High-frequency data link (HFDL) provided another long-range ACARS subnetwork that covered the north polar regions, which are not reached by Inmarsat signals. VHF Digital Link (VDL) Mode 2 provided a higher-speed subnetwork in continental airspace. More recently, Iridium provides a satellite subnetwork able to pass ACARS and ATC messages globally, including over both polar regions. These points will be elaborated in subsequent sections.

2.2 Voice Communications

2.2.1 VHF Voice

The modern VHF transceiver provides air–ground communications for all aircraft in controlled airspace. For transport aircraft (e.g., commercial airliners), the VHF transceiver is a minimum equipment list (MEL) item, meaning the aircraft cannot take off without the requisite number of operational units, in this case two. The reason for the dual-redundancy requirement is that the VHF transceiver is the primary means of communication with ATC.

The aeronautical VHF communication band covers the frequency range 118–136.975 MHz. VHF signals are limited to line of sight between the ground station and the aircraft, usually taken as a radius of approximately 120 nmi around the ground station. Aeronautical VHF voice operations are primarily limited by the radio horizon—the lowest unobstructed path angle between the aircraft and the ground station. Other factors include the altitude of the aircraft and the power of the transmission. Practically, aeronautical communications on a given voice frequency are limited to the extent of the ATC sector, as each new sector controller will be assigned a different channel. Reuse of a given channel is appropriate at about twice the usable radius.

The aeronautical VHF band is a protected spectrum, which means that any transmission not related to the safety and regularity of flight is prohibited. The wavelength of these signals is about 2 m or 90 in., which drives antenna size. The VHF band is divided into 760 channels spaced 25 kHz apart from 118.000 to 137.000 MHz. There is a 12.5 kHz guard band on each end of the allocated band. For 8.33 kHz operation, the VHF transceiver must be capable of tuning to one of 2280 channels spaced 8.33 kHz apart in the same frequency band. This capability was developed for European airspace when the number of ATC sectors (and, therefore, the number of radio channels assigned) grew beyond the ability to assign usable 25 kHz channels. The universally recognized emergency frequency is 121.500 MHz, which is monitored by all ATC facilities.

ICAO Annex 10 to the Convention on International Civil Aviation “International Standards and Recommended Practices, Aeronautical Telecommunications” promulgates the SARPs for voice and data communications in support of international air traffic services. In the case of voice ATC, the ICAO SARPs are generally followed for domestic ATC services as well.

The VHF voice audio is impressed upon the radio-frequency (RF) signal at the carrier frequency by using double-sideband (DSB) AM. This modulation method impresses the audio signal, typically 1–2 kHz, on the RF by varying the amplitude of the RF in proportion to the amplitude of the audio signal. In the frequency domain, the signal can be seen as a peak at the carrier frequency flanked by equal peaks above and below the sidebands. Upon reception, this signal is reconverted to audio and distributed to the headsets and the cockpit voice recorder. Figure 2.1 shows an AM signal both in the time domain, where the audio signal can be seen as riding on the RF carrier, and in the frequency domain, where the peaks representing the carrier and the sidebands can be easily seen.

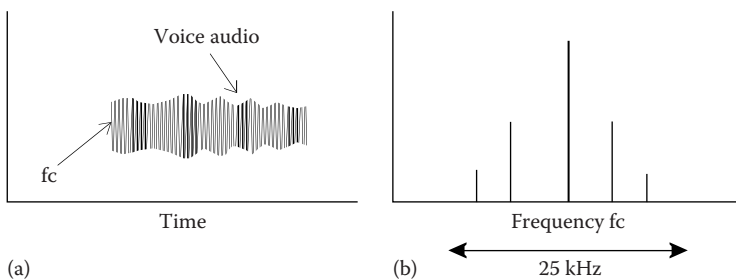


FIGURE 2.1 DSB AM voice signals: (a) time domain view and (b) frequency domain view.

Older VHF radios were tuned to a frequency (channel) from a remote radio control panel that housed a set of dials used to select each digit. The remote control panel was connected to the radio by 19 wires. Five lines, two of which were grounded for any selection, represented each decade digit of the frequency. This method originated from a scheme whereby the digit selection grounded a power connection to a motor at the radio. When the motor had driven a similar dial switch to its corresponding position, the ground was removed and the motor stopped. Presumably, the motor turned a tuning device (typically a variable capacitor). Later, non-motor-driven tuning methods kept the two-out-of-five grounded wire scheme until a digital data bus replaced it.

A modern VHF radio (e.g., one specified by ARINC characteristic 750) is connected to the radio control panel by the two wires of an ARINC 429 bus, which carry command words that perform all of the frequency select functions of the former 20 wires and others as well.

Frequency tuning is not the only element of the modern airborne VHF radio that has evolved. Whereas the motor-driven radio performed the DSB AM function using vacuum tubes or later transistors, the modern radio develops the same output signal in a radically different manner. Today's radio replaces the analog RF and modulator circuits with a high-speed microprocessor called a digital signal processor (DSP). The DSP works in conjunction with a high-speed analog-to-digital (abbreviated A to D or A/D) converter (ADC) that takes the voice audio input and converts it into a series of binary words, each representing the amplitude of the signal. A series of such samples, taken at a high enough rates, can faithfully represent the original analog waveform. This is the same method that records music onto a CD-ROM or MP3 file. A digital-to-analog (D/A) converter (DAC) performs the reverse function.

The DSP takes the digital representation of the audio input and algorithmically combines that information with the RF carrier signal and produces the DSB AM signal, which is sent to the power amplifiers. That was an easy sentence to write, but one that takes many lines of code to implement within the DSP. This method of combining information content, in this case voice audio, with the RF carrier at the selected frequency has tremendous flexibility. Within the constraints imposed by the power and speed of the DSP, the sample rates and sample size of the DAC/ADC, and other considerations, this architecture allows a great deal of flexibility. As will be seen, this type of radio is capable of producing not only DSB AM signals but other voice and data signals as well.

The terms "digital" and "analog" must be used with care. It is true to say that the modern avionics VHF radio is a "digital radio." It is also true to say that it handles voice signals digitally. However, to imply that we have "digital voice" is misleading. The signals propagated from the ground radio to the aircraft are the same DSB AM signals as the motor-tuned, vacuum-tube radio sent and received. Later, we will briefly discuss methods of sending voice over the RF in a digital manner.

2.2.2 HF Voice

HF voice is used for ATC communications in oceanic and remote airspace at various frequencies between 2.850 and 23.350 MHz with wavelengths between 100 and 10 m, respectively. The nature of the propagation of HF signals is such that it provides reliable communications at ranges of thousands of miles. This is possible because HF signals can be reflected by the bottom of the ionosphere at heights of about 70 miles. This effectively permits over-the-horizon or sky wave reception, not unlike the service performed by a satellite. At these frequencies, RF signals propagate with both a ground wave and a sky wave. The ground wave can give useful communication over the horizon, and the sky wave is usable well beyond that. Multiple hops are possible but are not reliable enough for aeronautical voice communication. Other characteristics of HF signals detract from its effectiveness for voice communications. For example, HF signals fade in a diurnal cycle and are susceptible to interference from solar activity. For example, approximately every 11 years, sunspot activity peaks causing significant effects on the ionosphere and on HF propagation.

The long wavelengths, comparable in length or longer than the aircraft, provide challenges as far as antenna placement is concerned. In the propeller-driven age, long wires from the tail forward were used. Later, long probes were mounted on the wingtips or tail. Now the HF antenna is typically installed in the

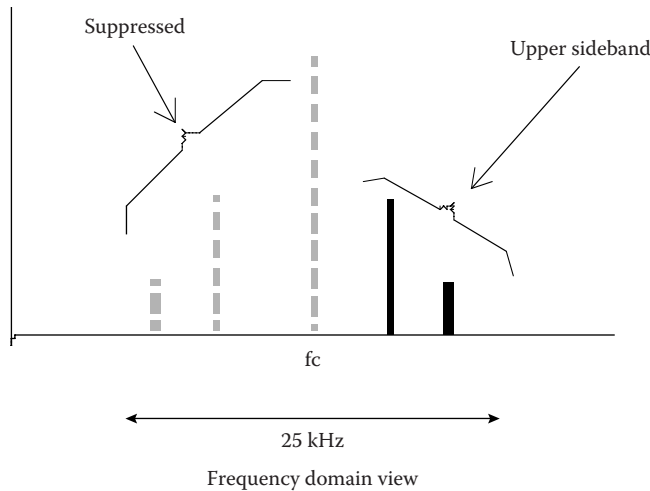


FIGURE 2.2 SSB voice signal.

forward edge of the vertical stabilizer, which is commonly made of composite materials. Ground station antennas can cover a football field.

HF voice is modulated onto the RF carrier using single-sideband (SSB) suppressed carrier modulation. Figure 2.2 shows the frequency domain view of an SSB signal. Note that only the upper sideband is used for aeronautical voice communications. Reliable HF communications requires the aircraft to transmit at 200 W peak envelope power (PEP) and the ground stations to transmit at as much as 5 kW PEP. SSB has the advantage over DSB AM of increased power in the intelligence-carrying signal as opposed to the carrier.

Flying in remote or oceanic airspace would require long hours of listening to the static-filled HF channel if it were not for selective calling (SELCAL), a technique that allows the flight crew to turn down the volume on the HF radio until the ground signals them using preselected tones. Special receive circuits are needed as these tones are not sent as SSB signals. When the preselected tones are recognized, the flight crew is alerted to come up on the HF channel.

2.2.3 Voice Developments

The proliferation of satellite telephone service on long-range aircraft has raised the question, “Why not just dial up ATC and talk to the controller?” Flight crews would like this method, but the reluctance is with the ANSPs. The management of frequencies in protected spectrum is, by now, a well-established procedure; the management of telephone numbers at each control position is not. There are other considerations, such as the use of nonprotected spectrum and the consequence of probable loss of protected spectrum, that inhibit a wholesale acceptance of telephone calls for ATC. Finally, the successful implementation of data link to the controller workstation environment has replaced the use of voice to the controller at such facilities for suitably equipped aircraft. However, carrying a voice radio remains a safety requirement.

Work is underway to create a third-party satellite voice service, similar to the HF voice service, to allow ATC satellite calls to/from the aircraft and the ground voice operator in remote and oceanic airspace. Such calls would terminate at the operator, where they would be converted to data to be sent to/from the controller.

Europe has demonstrated that the aeronautical VHF voice band can be expanded by the use of 8.33 kHz voice. The ICAO SARPs for VDL Mode 3 defines a true digital voice signal in space in which the audio signal is converted to a digital representation, is transmitted digitally across the air-ground VDL Mode 3 subnetwork, and is then reconverted to analog audio signals when it reaches its destination.

While VDL Mode 3 greatly expands the number of voice channels possible, the costs of replacing all VF radios, both airborne and ground, reduced support for this technique. This issue, along with other technical issues, caused this solution to be removed from further consideration.

The long-term possibility that broadband network connectivity to the aircraft may provide acceptable quality voice communication deserves some consideration for the far term. Meanwhile, DSB AM voice will remain the primary method of ATC voice communications for the foreseeable future.

2.3 Data Communications

2.3.1 ACARS Overview

Today, ACARS provides worldwide data link coverage. Five distinct air-ground subnetworks are available for suitably equipped aircraft: original VHF, Inmarsat satcom, HF DL, VDL Mode 2, and Iridium satellite. In order to understand the function of the avionics for ACARS, it is necessary to see the larger network picture. Figure 2.3 shows an overview of the ACARS network showing the aircraft, the four air-ground subnetworks, the central message processor, and the ground message delivery network.

The ACARS message-passing network is an implementation of a star topology with the central message processor as the hub. The ground message network carries messages to and from the hub, and the air-ground subnetworks all radiate from the hub. There are a number of ACARS network service providers, and their implementations differ in some details, but all have the same star topology.

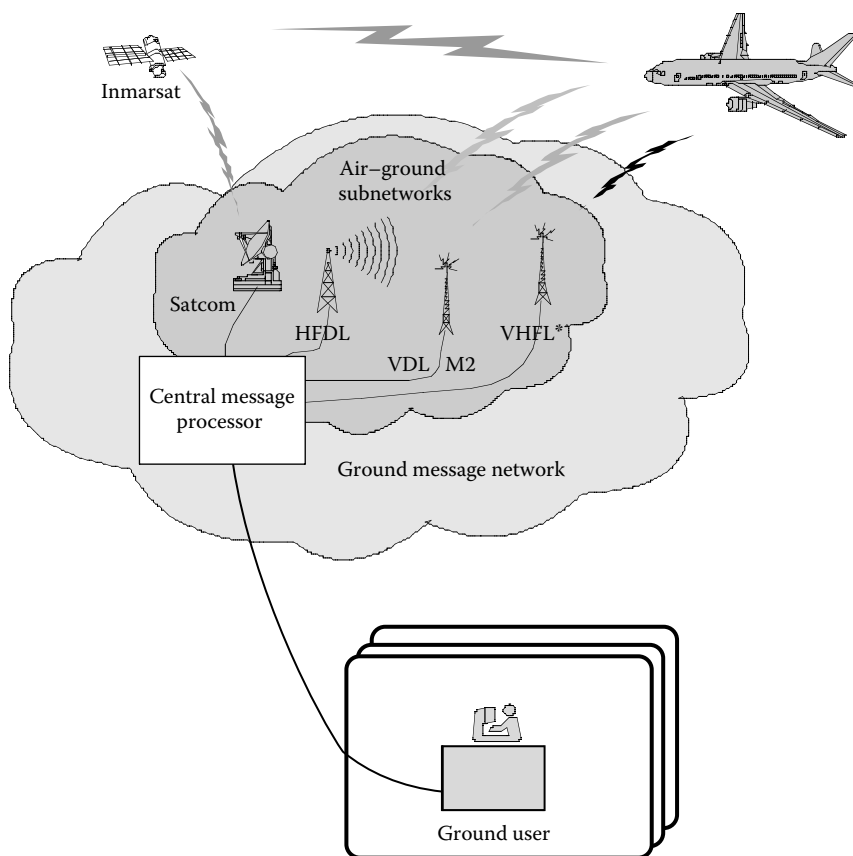


FIGURE 2.3 ACARS network overview. *VHFL, VHF data link; either ACARS or VDL M2.

Two data link service providers provide worldwide ACARS coverage, with several others providing regional coverage. Any given ACARS message can be carried over any of the air-ground subnetworks, a choice configured by the aircraft operator. It should be noted that ACARS is a character-oriented network, which means that only valid ASCII characters are recognized and that certain control characters are used to frame a valid message.

2.3.2 ACARS Avionics

The ACARS avionics architecture is centered on the management unit (MU), communications management unit (CMU), or communications management function (CMF), which acts as an onboard router. All air-ground radios connect to the MU or CMU/CMF to send and receive messages. The CMU/CMF is connected to all of the various radios that communicate to the ground. Figure 2.4 illustrates the avionics architecture.

2.3.3 ACARS Management Unit

The MU or CMU/CMF acts as the ACARS router onboard the aircraft. All messages to or from the aircraft, over any of the air-ground subnetworks, pass through the MU or CMU/CMF. Although the MU or CMU/CMF handles all ACARS message blocks, it does not perform a message-switching function because it does not recombine multiple message blocks into a “message” prior to passing it along. It passes each message block in accordance with its “label” identifier, and it is up to the receiving end system (ES) to recombine message blocks into a complete message. The original OOOI messages were formatted and sent to the MU from an avionics unit that sensed various sensors placed around the aircraft and determined the associated changes of state. In the modern transport aircraft, many other avionics units send and receive routine ACARS messages.

The multifunction control and data unit (MCDU), along with the printer, is the primary ACARS interface to the flight crew. Other units, such as the FMS or the air traffic services unit (ATSU), will also interact with the crew for FANS messages. The vast majority of data link messages today are downlinks automatically generated by various systems on the airplane. The MU/CMU/CMF identifies each uplink message block and routes it to the appropriate device. Similarly, it takes each downlink, adds associated

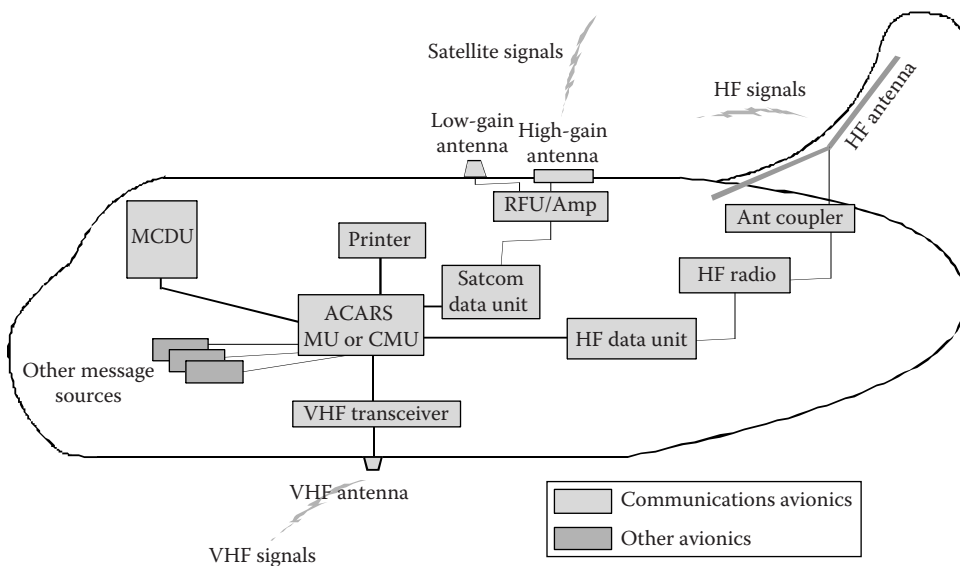


FIGURE 2.4 ACARS avionics architecture.

aircraft information such as the tail number, and sends it to one of the air-ground subnetworks. The latest avionics for each of the four subnetworks accepts an ACARS block as a data message over a data bus, typically ARINC 429. The subnetwork avionics will then transform the message block into the signals needed to communicate with the ground radio. Each subnetwork has its own protocols for link layer and physical layer exchange of a data block.

2.3.4 VHF Subnetwork

The original VHF subnetwork that was pioneered in 1978 uses the same 25 kHz VHF channels used by ATC and aeronautical operational communication (AOC) voice; the signal in space is sometimes called plain old ACARS (POA) for reasons that will become clearer when we discuss VDL Mode 2. The VHF subnetwork uses a form of frequency shift keying (FSK) called minimum shift keying (MSK) wherein the carrier is modulated with either a 1200 or 2400 Hz tone. Each signaling interval represents one bit of information, so the 2400 baud (i.e., rate of change of the signal) equals the bit rate of 2400 bps. After initial synchronization, the receiver then can determine whether a given bit is a one or a zero.

VHF ACARS uses the carrier-sensed multiple access (CSMA) protocol to reduce the effects of two transmitters sending a data block at the same or overlapping times. CSMA is nothing more than the automated version of voice radio protocols wherein the speaker first listens to the channel before initiating a call. Once a transmitter has begun sending a block, no other transmitter will “step on” that transmission. The VHF ACARS subnetwork is an example of a connectionless link layer protocol in that the aircraft does not “log in” to each ground station along its route of flight. The aircraft does initiate a contact with the central message processor, and it does transmit administrative message as it changes subnetworks. A more complete description of the POA signal and an ACARS message block as it is transmitted over a VHF channel can be found in ARINC 618, Appendix B.

In congested airspace, such as the northeastern United States or Europe, multiple VHF ACARS channels are needed to carry the message traffic load. For example, in the Chicago area, 10 channels are needed and a sophisticated frequency management scheme has been put in place, which automatically changes the frequency used by individual aircraft to balance the loads.

Initial ACARS MUs worked with VHF radios that were little modified from their voice-only cousins. The ACARS modulation signal was created as two-tone audio by the MU (e.g., ARINC 724 MU) and sent to the radio (e.g., ARINC 716 VHF radio), where it modulated the RF, just as voice did from a microphone. Later evolutions of the ACARS interface between the CMU (e.g., ARINC 758 CMU) and the latest radio (e.g., ARINC 750 VDR [VHF data radio]) sent ACARS message blocks between the CMU and the radio over a serial data bus (i.e., ARINC 429 Digital Information Transfer System [DITS]), and the radio modulated the RF directly from the data.

2.3.5 Satcom

The first satellite ACARS subnetwork uses the Inmarsat constellations. In the I-3 constellation, four satellites in geosynchronous orbit provide global beam and spot beam coverage of the majority of the globe (up to about 82° latitude) with spot beam coverage over the continents. In the I-4 constellation, three satellites in geosynchronous orbit provide global beam and spot beam of the major landmasses and northern oceans. The Inmarsat constellation provides telephone circuits as well as data link, so it uses a complex set of protocols over several different types of channels using different signals in space. In the aeroclassic services, a packet channel is used to send and receive ACARS or cabin packet data messages. The packet channel is established when the avionics satellite data unit (SDU) logs on to a satellite ground earth station (GES). Each frame is acknowledged between the SDU and GES at the data link layer. Any ACARS data link message block generated by the C/MU for transfer over the satcom subnetwork is sent to the SDU for transfer over this channel to the GES, where it is then forwarded to the ACARS central message processor. The message forwarding function requires advance coordination for appropriate

routing and billing to take place. In the SwiftBroadband data service, which is a 432 kbps packet data service over the I-4 constellation, the ACARS or cabin packet data messages will be sent on available IP bandwidth as connectionless datagrams. The Inmarsat satellite access nodes (SANs) route the message on the ground to appropriate gateway services.

The Inmarsat aeroclassic services operate in the L-band, around 1 GHz on frequencies reserved for aeronautical mobile satellite (route) services, or AMS(R)S, which are protected for safety and regularity of flight. Satcom avionics have been purpose built, meaning that they did not evolve from the previous use of L-band radios for voice as VHF ACARS and (as we shall see) HF DL radios evolved from voice radios. In the Aero classic services, the RF unit (RFU), along with high-gain and low-noise amplifiers and the diplexer, sends and receives signals over the various L-band channels defined for Inmarsat services.

In 1995, the use of ACARS messages over satcom was certified for use in the south Pacific for long-range ATC communications with the FAA (Oakland Center), Fiji, New Zealand (Auckland Center), and Australia (Brisbane Center). The message set used was called the FANS-1 message set and mirrored HF voice messaging in oceanic airspace. Boeing 747-400 aircraft were the first to implement FANS-1, but long-range Airbus aircraft soon followed with the FANS-A implementation. Since that time, FANS-1/A has been implemented by many CAAs around the world where the message set supports local ATC procedures.

2.3.6 HF DL

The HF DL ACARS subnetwork uses channels in the HF voice band. The HF DL radio can be a slightly modified HF voice radio connected to the HF data unit (HFDU). Alternatively, an HF data radio (HFDR) can contain both voice radio and data link functions. In either case, the HF communication system must be capable of independent voice or data operation.

HF DL uses phase-shift modulation (PSK) and time-division multiple access (TDMA). A 32 s frame is divided into 13 slots, each of which can communicate with a different aircraft at a different data rate. Four data rates (1800, 1200, 600, and 300 bps) use three different PSK methods (8PSK, 4PSK, and 2PSK). The slowest data rate is affected by doubling the power of the forward error-correcting code. All of these techniques (i.e., multiple data rates, forward error correction, TDMA) are used to maximize the long-range properties of HF signals while mitigating the fade and noise inherent in the medium. Twelve HF DL ground stations provide worldwide coverage, including good coverage over the North Pole but excluding the south polar region. More details on HF DL may be found in ARINC 753: HF Data Link System.

The need for a large antenna, plus the fact that even a quarter-wavelength antenna is problematic, necessitates an antenna coupler that matches the impedance of the feed line to the antenna. The RFU, whether it is a separate unit or incorporated in the HFDR, combines the audio signal representing the data modulation with the carrier frequency, suppresses the carrier and lower sidebands with appropriate filtering, and amplifies the resultant signal.

2.3.7 VDL Mode 2

VDL Mode 2 operates in the same VHF band as POA. Four channels have been reserved worldwide for VDL Mode 2 services. Currently, the only operating frequency is 136.975 MHz. VDL Mode 2 uses differential 8-level phase-shift keying (D8PSK) at a signaling rate of 10.5 kbaud to modulate the carrier. Since each phase change represents one of eight discernible phase shifts, three bits of information are conveyed by each baud or signal change; therefore, the data rate is 31.5 kbps. With about 10 times the capacity of a POA channel, VDL Mode 2 has the potential to significantly reduce channel congestion for ACARS. CSMA is used for media access, but a connection-oriented link layer protocol called the aviation VHF link control (AVLC) is established between the VDR and the ground station. ACARS over AVLC (AOA) is the term used to distinguish ACARS message blocks from other data packets that can also be passed over AVLC. By using AOA, an aircraft equipped with VDL Mode 2 may take advantage of a higher-speed VHF link without any changes to the AOC messages passed to or from the aircraft.

It should be noted that VDL Mode 2 has been implemented in accordance with the ICAO SARPs as a subnetwork of the ATN. The ARINC 750 radio is capable of supporting 25 and 8.33 kHz voice, POA, and AOA. It may only be used for one of these functions at any given time.

2.3.8 Iridium

The Iridium system is capable of connecting telephone calls and data messages to and from aircraft in flight anywhere on earth. ACARS uses the short burst data (SBD) capability of the Iridium system to carry ACARS blocks between the MU or CMU and the central processor of the airline-selected ACARS service provider.

The Iridium constellation consists of 66 satellites in low earth orbits (LEO) at about 485 miles altitude, in six polar orbital planes. LEO satellites travel rapidly across the sky relative to a ground or airborne subscriber. The connection from the aircraft for telephone calls and the point-to-point protocol (PPP) connection for data are maintained by cross-linking between satellites and then downlinking to the Iridium gateway in Arizona. LEO satellites require less transmit power from the avionics than geosynchronous satellite data links.

2.3.9 ATN

2.3.9.1 ATN History and Overview

In the 1980s, the ICAO Air Navigation Commission (ANC) recognized the need to assure commonality among future data links used for air traffic communications. In 1989, the ANC tasked the secondary surveillance radar (SSR) improvement and collision avoidance panel (SICASP) to develop material to assure that commonality. By 1991, the automatic dependent surveillance panel (ADSP) had produced the *Manual of Data Link Applications*, defining message sets for use by ANSPs. In 1997, the ANC approved SARPs for the ATN as the framework for all future ATC data communications.

2.3.9.2 ATN Architecture

The ATN architecture is based on the OSI model for data communications that was published by the ISO. This architecture, as shown in the following figure, identifies seven layers that provide flexibility in implementation while maintaining an orderly flow of message traffic to and from the ES. Other basic characteristics of the ATN include bit-oriented messaging and packet-switched routing.

The ATN is based on multiple air-ground subnetworks, to facilitate communication to a wide variety of aircraft in widely varying airspace, and multiple ground-ground networks to allow for independent domains for air navigation and other service providers.

The structure of the ATN includes ESs, which originate and receive ATN messages with each having a seven-layer ISO stack, and intermediate systems (IS) also called routers, which assure that message packets get to the proper destination ES within the domain. If a message is directed to an ES outside the domain, it is directed to a boundary intermediate system (BIS) for transmission to the proper domain.

The aforementioned architecture applies to all ground and airborne ESs. For aircraft in flight, the ATN connection is maintained by one or more of the ATN subnetworks. For ground ESs, normal telecommunications infrastructure may be used.

2.3.9.3 ATN Subnetworks

At the data link layer (layer 2) and the physical layer (layer 1), the ATN includes SARPs for the following air-ground data links:

- VDL
- Geosynchronous satellite (satcom)
- HF data link (HFDL)
- Iridium satellite

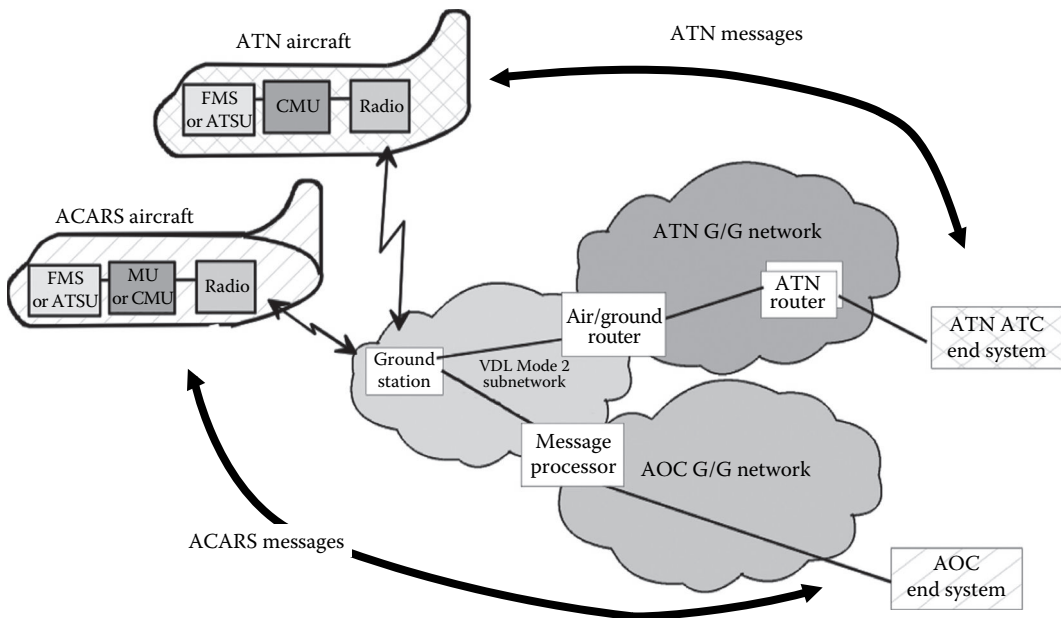


FIGURE 2.5 VDL Mode 2 Subnetwork supports both ACARS and ATN.

Each of these subnetworks is implemented with a unique RF modulation and protocol. VDL operates line of sight and therefore requires multiple ground stations to assure continuous coverage. The other three subnetworks may be used in remote and oceanic airspace, but each has its unique advantages and disadvantages.

2.3.9.4 VDL Subnetwork

As of this writing, the VDL Mode 2 is in operation and is the only ATN air-ground subnetwork being used for ATN message traffic. In Europe, VDL Mode 2 is being used for operational ATC data link messages, while in the United States, ATC data link trials are underway providing departure clearances.

Figure 2.5 shows how the VDL Mode 2 subnetwork has been designed to carry both ACARS messages and ATN messages. VDL Mode 2 is a bit-oriented data link layer protocol, which, in the case of AOA, happens to be carrying ACARS message blocks. ACARS message blocks are directed to the message processor for forwarding over the AOC ground-ground network. ATN packets are directed to an air/ground router that forwards them to an ATN router for delivery via the ATN ground-ground network.

2.3.10 Data Communications Developments

The implementation of broadband Internet connections in the aircraft while in flight has the potential to provide versatile, fast, and cheap connectivity between the aircraft and the ground. Since the earliest voice radio links, through all of the ACARS air-ground subnetworks, air-ground communications has been so specialized that the equipment has been specially designed and built at great cost. If broadband Internet (meaning TCP/IP) connectivity can be made reliable and secure, there is no reason this medium could not be made usable for air-ground data link communication. The definition of the IPS for the ATN has the potential to add near-universal connectivity for ATC communications.

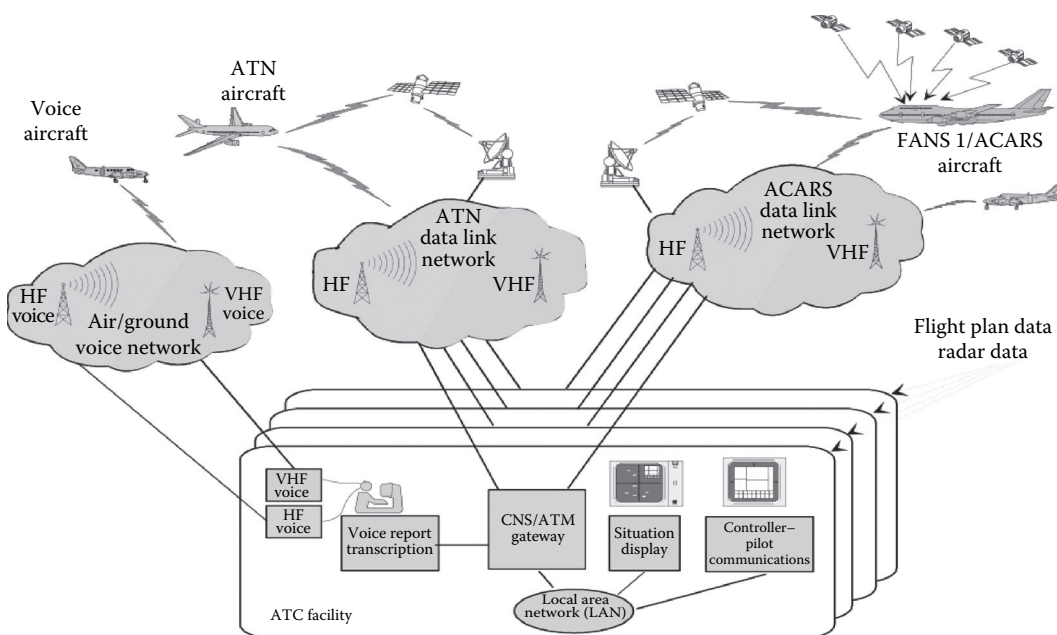


FIGURE 2.6 National ATC facility supporting multiple voice and data networks.

The trend in the telecommunications industry is toward high-speed, high-capacity, general-purpose connectivity. For example, fiber optic links installed to carry cable TV are being used, without significant change, as Internet connections or telephone lines. Sophisticated high-capacity RF modulation techniques are permitting the broadcast of digital signals for high-definition TV and radio. Mobile telephone technology carries digital voice and data messages over the same network. The Internet itself carries far more than the text and graphics information it was originally designed to carry.

Figure 2.6 shows a notional ATC facility of the future, which is able to use voice, ATN data link, and FANS-1/A data links to communicate with suitably equipped aircraft traversing its airspace. The transfer of the majority of routine communications to data link, often with automatic exchanges between the ground and the aircraft, will reduce workload for aircrews and controllers. This will increase the number of aircraft participating in air traffic management (ATM) that will allow benefits for all involved: airlines, aircrews, controllers, and airspace managers.

2.4 Summary

The airlines will continue to increase their dependence on air-ground data link to send and receive information necessary to efficiently operate their fleets. ATC will increase its dependence on air-ground communications, even as the number of voice transactions is reduced. Looking 10–20 years ahead, data link will increasingly be used for ATC communications. If the concept of ATM is to become the rule instead of the exception, the ground automation systems and the FMSs will no doubt be in regular contact, exchanging projected trajectory, weather, traffic, and other information. Voice intervention will be minimal and likely still be over DSB AM in the VHF band.

The modern transport aircraft is becoming a flying network node that will inevitably be connected to the ground for seamless data communications. It's only a matter of time and ingenuity. When that happens, presuming there is sufficient bandwidth, availability, and reliability for each use, many applications will migrate to that link.

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Navigation

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3.1 Introduction

“Navigation” is the determination of the position and velocity of a moving vehicle, on land, at sea, in the air, or in space. The three components of position and the three components of velocity make up a six-component *state vector* whose time variation fully describes the translational motion of the vehicle. With the advent of the global positioning system (GPS), surveyors use the same sensors as navigators but achieve higher accuracy as a result of longer periods of observation and more complex postprocessing.

In the usual navigation system, the state vector is derived on board, displayed to the crew, recorded on board, or transmitted to the ground. Navigation information is usually sent to other onboard subsystems such as waypoint steering, communication control, display, weapon-control, and electronic warfare (emission detection and jamming) computers. Some navigation systems, called *position-location systems*, measure a vehicle’s state vector using sensors on the ground or in another vehicle. The external sensors usually track passive radar returns or a transponder. Position-location systems usually supply information to a dispatch or control center.

The term *guidance* has two meanings, both of which are different than *navigation*. In the *first*, steering is toward a destination of known position from the vehicle’s present position. The steering equations are derived from a plane triangle for nearby destinations or from a spherical triangle for distant destinations. In the *second* definition, steering is toward a destination without calculating the state vector explicitly. A guided vehicle *homes* on radio, infrared, or visual emissions. Guidance toward a *moving* target is usually of interest to military tactical missiles in which a steering algorithm assures impact within the maneuver and fuel constraints of the interceptor. Guidance toward a *fixed* target involves beam riding, as in the instrument landing system (ILS), Section 3.5.

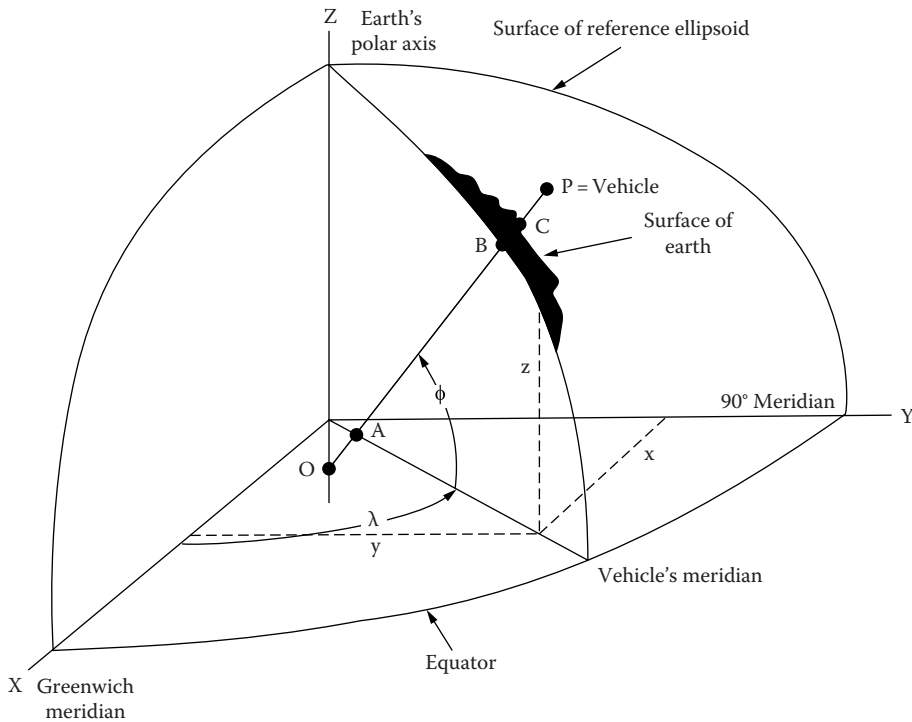


FIGURE 3.1 Latitude–longitude–altitude and XYZ coordinate frames. *Note:* ϕ , geodetic latitude; OP is normal to the ellipsoid at B ; λ , geodetic longitude; $h = BP$ = altitude above reference ellipsoid = altitude above mean sea level.

The term *flight control* refers to the deliberate rotation of an aircraft in three dimensions, which causes its velocity vector to change direction.

3.2 Coordinate Frames

Navigation is with respect to a coordinate frame of the designer's choice. For navigation over hundreds of kilometers (e.g., helicopters), various map grids exist whose coordinates can be calculated from latitude and longitude. NATO helicopters and land vehicles use a Universal Transverse Mercator grid. Long-range aircraft navigate relative to an Earth-bound coordinate frame, the most common of which are (Figure 3.1) as follows:

1. Latitude–longitude–altitude, measured with respect to a reference ellipsoid. The most useful reference ellipsoid is described in WGS-84 (1991). Longitude becomes indeterminate in polar regions, rendering these coordinates unsuitable there.
2. Earth-centered rectangular (xyz). These coordinates are valid worldwide; hence, GPS calculates in them and often converts to latitude–longitude–altitude for readout.

3.3 Categories of Navigation

Navigation systems can be categorized as absolute, dead reckoning, or mapping. *Absolute navigation systems* measure the state vector without regard to the path travelled by the vehicle in the past. These are of two kinds: radio systems (Section 3.5) and celestial systems (Section 3.6). Radio systems consist of a network of transmitters (sometimes transponders) on the ground or in satellites. An aircraft detects the transmissions and computes its position relative to the known positions of the stations

in the navigation coordinate frame. The aircraft's velocity is measured from the Doppler shift of the transmissions or from a sequence of position measurements.

The second absolute system, celestial (Section 3.6), measures the elevation and azimuth of celestial bodies relative to the local level and true north. Electronic star sensors are used in special-purpose high-altitude aircraft and in spacecraft. Manual celestial navigation was practiced at sea for millennia (Bowditch, 1995).

Dead-reckoning navigation systems derive their state vectors from a continuous series of measurements beginning at a known initial position. There are two kinds: those that measure heading and either speed or acceleration (Section 3.4) and those that measure emissions from continuous-wave radio stations whose signals create ambiguous “lanes” (Section 3.5). Dead-reckoning systems must be *updated* as errors accumulate and if electric power is lost. The only radio dead-reckoning system, Omega (Section 3.5), was decommissioned in 1997.

Lastly, *mapping navigation systems* observe and recognize images of the ground, profiles of altitude, sequences of turns, or external features (Section 3.7). They compare their observations to a stored database. They are mostly used in cruise missiles.

3.4 Dead Reckoning

The simplest dead-reckoning systems measure aircraft heading and speed, resolve speed into the navigation coordinates, and then integrate to obtain position (Figure 3.2). The oldest heading sensor is the magnetic compass: a magnetized needle, an electrically excited toroidal coil (called a *flux gate*), or an electronic magnetometer, as shown in Figure 3.3. Magnetometers are Hall effect or magnetoresistors that measure the change in electrical resistance of a magnetic substance as the magnetic field changes. Three orthogonal magnetoresistors are usually mounted on a circuit board (Figure 3.3) that measures the direction of the Earth's field to an accuracy of about 2° at a steady aircraft speed. Hall-effect

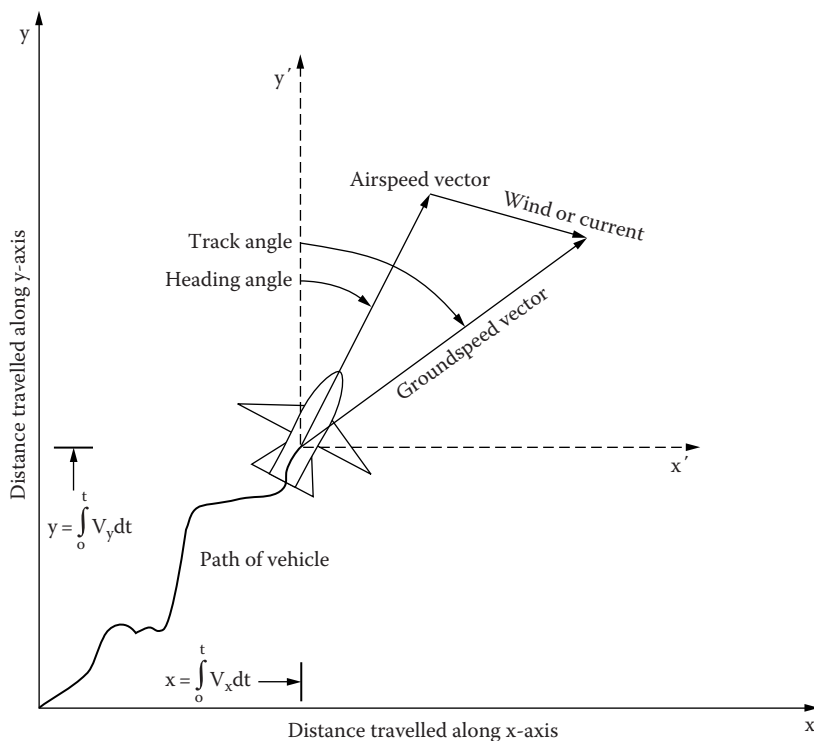


FIGURE 3.2 Geometry of dead reckoning.

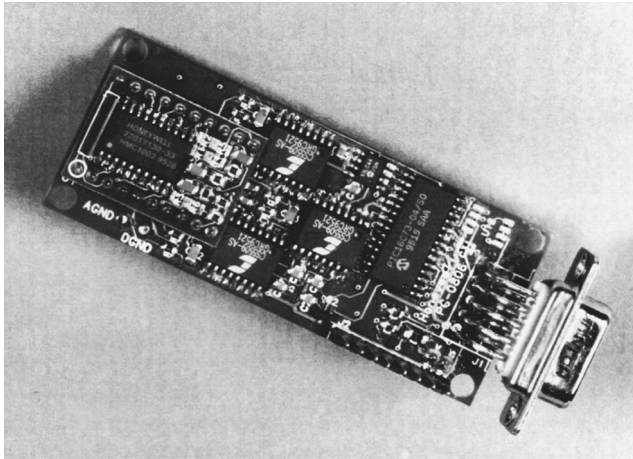


FIGURE 3.3 Circuit board from 3-axis digital magnetometer. A single-axis sensor chip and a 2-axis sensor chip are mounted orthogonally at the end opposite the connector. The sensor chips are magnetoresistive bridges with analog outputs that are digitized on the board. (Photo courtesy of Honeywell, Morristown, NJ.)

magnetometers are less common in aircraft. The horizontal component of the magnetic field points toward *magnetic north*. The angle from true to magnetic north is called *magnetic variation* and is stored in the navigation computers as a function of position over the region of anticipated travel (Quinn, 1996). Magnetic deviations caused by iron and motors in the vehicle can exceed 30° and must be compensated in the navigation computer.

A more complex heading sensor is the *gyrocompass*, consisting of a spinning wheel whose axle is constrained to the horizontal plane by a pendulous weight. The aircraft version (more properly called a *directional gyroscope*) holds any preset heading relative to the Earth, drifts at more than 50°/h, and must be reset periodically. Attitude and heading reference systems (AHRS) use inexpensive gyroscopes (some built on silicon chips as vibrating beams) and silicon accelerometers that are coupled to magnetic compasses to reduce maneuver-induced errors and long-term drift.

The usual speed sensor on an aircraft or helicopter is a *pitot tube* that measures the dynamic pressure of the air stream from which airspeed is derived in an *air-data computer*. To compute ground speed, the velocity of the wind must be vectorially added to that of the aircraft (Figure 3.2). Hence, unpredicted wind will introduce an error into the dead-reckoning computation. Most pitot tubes are insensitive to the component of airspeed normal to their axis, called *drift*. Pitot tubes must be heated to prevent ice from blocking the orifices.

A Doppler radar measures the frequency shift in radar returns from the ground or from water below the aircraft, from which ground speed is inferred. Multibeam Doppler radars can measure all three components of the aircraft's velocity relative to the reflecting surface below. Doppler radars are widely used on military helicopters because of the difficulty of locating pitot tubes on a vehicle that can fly sideways or backward.

The most accurate dead-reckoning system is an *inertial navigator* (Figure 3.4) in which precise accelerometers measure the vehicle's acceleration, while precision gyroscopes measure the orientation of the accelerometers. An onboard computer resolves the accelerations into navigation coordinates and integrates the components of acceleration once to obtain velocity and again to obtain position. When spinning-wheel gyroscopes were used, they and the accelerometers were mounted in servoed gimbals that angularly isolated them from rotations of the aircraft. Since about 1990, only super-precision star trackers and naval navigators use gimbals. All modern aircraft inertial navigators fasten the gyroscopes and accelerometers directly to the aircraft ("strap down"), thereby exposing these instruments to the angular rates and angular accelerations of the aircraft.

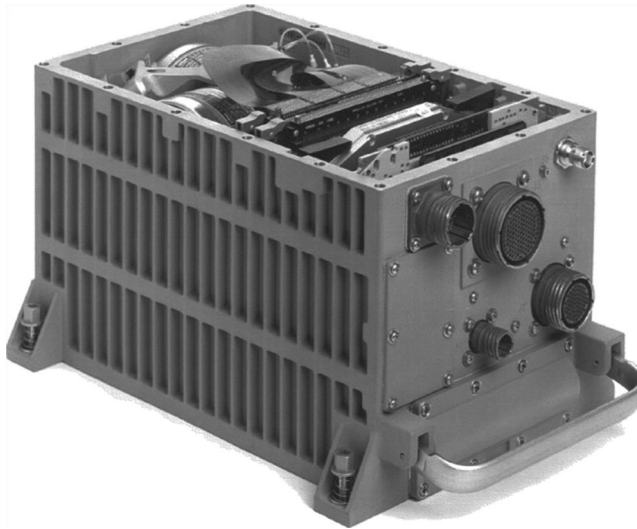


FIGURE 3.4 GPS-inertial navigator. The inertial instruments are mounted at the rear with two laser gyroscopes and electrical connectors visible. The input-output board is next from the rear; it excites and reads the inertial sensors. The computer board is next closest to the observer and includes MIL-STD-1553 and RS-422 external interfaces. The power supply is in front. Between them is the single-board shielded GPS receiver. Round connectors on the front are for signals and electric power. A battery is in the case behind the handle. Weight 10 kg, power consumption 40 W. This navigation set is used in the F-22 and many other military aircraft and helicopters. (Photo courtesy of Northrop-Grumman Corporation, Falls Church, VA.)

Attitude is computed by a *quaternion* algorithm (Kayton and Fried, 1997, pp. 352–356) that integrates measured angular increments in three dimensions. A slower algorithm calculates the navigation coordinates. Inertial systems measure aircraft orientation within 0.1° for steering and pointing. Most accelerometers consist of a gram-sized proof mass that is mounted on a flexure pivot. The least expensive ones measure the deflection of the proof mass; the most precise accelerometers restore the proof mass to null electrically, thus not relying on the structural properties of the flexure. In the newest accelerometers, the proof masses are etched into silicon chips.

The oldest gyroscopes contained metal wheels rotating in ball bearings or gas bearings that measured angular velocity or angular increments relative to *inertial space*. More recently, gyroscopes contained rotating, vibrating rings whose frequency of oscillation measured the instrument's angular rates. The most precise gyroscopes are evacuated cavities or optical fibers in which counterrotating laser beams are compared in phase to measure the sensor's angular velocity relative to *inertial space* about an axis normal to the plane of the beams. Vibrating hemispheres and rotating, vibrating bars are the basis of some navigation-quality gyroscopes (drift rates less than $0.1^\circ/\text{h}$).

Fault-tolerant configurations of cleverly oriented redundant gyroscopes and accelerometers (typically four to six of each) detect and correct sensor failures. Inertial navigators are used in long-range airliners, in business jets, in most military fixed-wing aircraft, in space boosters and entry vehicles, and in manned spacecraft.

3.5 Radio Navigation

Scores of radio navigation aids have been invented and many of them have been widely deployed, as summarized in Table 3.1. The most precise is the GPS, a network of 24 satellites and 4 or more on-orbit spares, 17 ground monitor stations for monitoring, a master control station, and its backup station.

TABLE 3.1 Worldwide Radio Navigation Aids for Aviation

System	Frequency		Number of Stations	Number of Aeronautical Users
	Hz	Band		
Loran-C/Chaika	100 kHz	LF	50	10,000
Beacon ^a	200–1600 kHz	MF	4000	130,000
Instrument landing System (ILS) ^a	108–112 MHz	VHF	1500	200,000
	329–335 MHz	UHF		
VOR ^a VORTAC	108–118 MHz	VHF	1500	200,000
SARSAT/COSPAS	243,406 MHz	UHF	5 satellites	200,000
JTIDS	960–1213 MHz	L	None	500
DME ^a	962–1213 MHz	L	1500	120,000
Tacan ^a	962–1213 MHz	L	120	15,000
Secondary surveillance Radar (SSR) ^a	1030, 1090 MHz	L	800	250,000
GFS-GLONASS	1227, 1575 MHz	L	24 + 24 satellites	200,000
Radar altimeter	4200 MHz	C	None	40,000
MLS ^a	5031–5091 MHz	C	5	200,000
		X		
Airborne Doppler radar	13–16 GHz	Ku	None	40,000
SPN-41 carrier-landing monitor	15 GHz	Ku	25	1600
SPN-42/46 carrier-landing radar	33 GHz	Ka	25	1600

^a Standardized by International Civil Aviation Organization.

An aircraft derives its 3D position and velocity from one-way ranging signals received from four or more satellites. Each satellite transmits a civil frequency (L1 = 1575.42 MHz), a military frequency (L2 = 1227.60 MHz) with a superimposed L2C civil modulation, and on the newest satellites, a second civil frequency (L5 = 1176.45 MHz). Each spacecraft carries multiple precise atomic clocks (one part in 10E13), whereas the aircraft carry temperature-controlled quartz clocks whose accuracy is 10E8. The largest source of error is delay as the radio signals pass through the ionosphere. The delay is frequency dependent. Hence, by receiving any two of L1, L2, and L5, an aircraft corrects the ionospheric delay to first order. By receiving all three, it can correct the ionospheric delay to second order. Misra and Enge (2001) and Parkinson and Spilker (1996) describe the GPS in detail.

GPS offers better than 20 m ranging errors on a moving aircraft to civil users and 5 m ranging errors to military users. Single-frequency receivers were available in 2013 for less than \$100. GPS receivers are built into cell phones at 100 m accuracy without the ability to track at aircraft speeds.

GPS provides continuous worldwide navigation for the first time in history. It has displaced dead reckoning on many aircraft and reduced the cost of most navigation systems. Figure 3.5 is an artist's drawing of a GPS Block 2F spacecraft, first launched in 2010. During the 1990s, Russia deployed a satellite navigation system, incompatible with GPS, called GLONASS (Urlichich, 2011, May 2012). In 2013, more than 20 operating GLONASS were in orbit. In 2013, the European Union had launched test versions of its own navigation satellite system, called Galileo, which will offer free and paid services (Hein et al., 2003; Anonymous, 2009). The United States plans a major upgrade of GPS by 2015 to reduce vulnerability to jamming (Enge, 2004). The International Global Positioning Service (IGS) issues post-processing (six hour delay and longer) corrections to satellite positions to centimeter accuracy (Novatel, 2014).

Differential GPS (DGPS) employs ground stations at known locations that receive GPS signals and transmit measured ranging errors on a radio link to nearby aircraft via geosynchronous satellites or via Mode-S transponders (1090 MHz). DGPS improves accuracy (centimeters for fixed observers close to a DGPS station) and, more importantly for aeronautical use, detects faults in GPS satellites immediately. Status messages from the satellites can be hours out of date. In 2003, the United States created a nationwide