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One Hundred Years of Aircraft Electronics

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I. Introduction

THE purpose of this paper is to review the progress of aircraft electronics during the hundred years since the first controlled flight by the Wright brothers and to project into the first decades of the 21st century. The paper makes occasional reference to manned spacecraft and none to boosters, which are arts unto themselves. Electronics for aircraft are often called "avionics." Electronics for spacecraft and automobiles are either called avionics or "astrionics" and "vetronics," respectively.

Human flight was almost entirely invented in Europe after thin-wall steel tubing became available in the 1880s. Among the first recorded flights are Otto Lilienthal's unpowered hang gliders in the 1890s and Clement Ader's steam-powered hang gliders. The Wright brothers, in far off 1903 America, were the first to control a gasoline-powered, wood-and-wire biplane in three axes, by use of a front-mounted elevator for pitch control, a marine-inspired rudder for side slip, and wing-warp roll control (revived in 1977 for the human-powered Gossamer Condor). The Wrights used a lever for pitch control and a hip harness for roll control. At first, they coupled the rudder to wing warp, but later added a second lever for the rudder.[1] By the early 1910s, Farman's and Bleriot's aircraft were in the configuration we know today: aft rudder and tailplane, hinged control surfaces, pilot's stick and rudder pedals, tractor propeller, and gasoline engine. After Europe self-destructed during World War I, the focus of aviation innovation moved to the United States and has remained here ever since.

For decades, the only electrical equipment on an aircraft were the engine's magnetos that fire the spark plugs. Cockpit instruments were vacuum operated from the engine's intake manifold: the first spinning-wheel vacuum gyroscope appeared in 1914. Power boost was by aerodynamic tabs or by hydraulics[1] pressurized from an engine-driven pump. Vacuum-tube electronics in radars and navigation sets were added during World War II. They were heavy, expensive, and unreliable, and, hence, purchased only for military-essential missions. In the 1960s, transistorized vhf omnirange [(VOR), Sec. II.B.1] navigation and communications (just above 100 MHz), instrument landing system (ILS) receivers, and transponders became affordable even by owners of light aircraft. Figure 1 shows a cockpit circa 1975 with conventional gauges and a central avionics "stack" containing all of the radios (some of which are of 1990s vintage in this photograph).

The integrated-circuit computer chip and memory chip created today's avionics. Complex autopilot functions, waypoint steering, and electronic displays became commonplace in the 1980s; self-test, stored digital charts and approach plates in the 1990s; and passenger services in the 2000s. Indeed government rules prohibit aircraft from entering high-density airspace and preferred over-ocean airways without suitable avionics. In the year 2003, avionics are more expensive than automotive or consumer electronics because of 1) the need to conform to safety regulations that protect high-value vehicles and occupants and 2) low-production volume; an avionics manufacturer produces perhaps 500 devices of a single type in a year, fewer than a cell-phone manufacturer produces in an hour. Hence, avionics development costs are a substantial fraction of the unit cost. The development cost of military avionics is often assigned to a different budget than the production costs so that amortization is unnecessary.

Spacecraft electronics are more expensive still because individually pedigreed parts and intensive testing are needed for vehicles where servicing is either impossible or immensely costly.

Jet aircraft were not employed commercially until the British Comet flew in 1952. Supersonic aircraft did not operate routinely until the century-series American fighters of the early 1960s. There were no spacecraft until 1956; their avionics content was minimal and analog until the U.S. Gemini in 1967. Military rockets were unguided and had no avionics at all except that the German V-1 cruise missile and V-2 ballistic missile had primitive analog guidance systems (Ref. 2, pp. 234 and 317).

Since 1995, avionics have been undergoing their most rapid period of growth since the digital revolution of the 1970s. In Sec. II advances in avionic subsystems are described. In Sec. III, advances in the systems that interconnect the subsystems are described. In Sec. IV, predications are made for 20 years into the future. Some overall conclusions are drawn in Sec. V.

A comprehensive treatment of this topic would require several textbooks. Hence, the author selected key issues from his personal experience.

II. Avionic Subsystems

A. Electric Power

Avionics require a source of electric power. Many avionic devices are safety critical, for example, flight-control computers, and even more are mission critical, for example, navigation sets and landing aids, each requiring its own level of reliability. The electrical system of a small aircraft resembles that of an automobile. An alternator on each engine contains a built-in rectifier that supplies direct current, usually at 28 V. (Single-engine aircraft sometimes have dual alternators.) A regulator controls the excitation current of the alternator to maintain a preset steady voltage as the engine's speed changes. Overvoltage and undervoltage indicators are provided. The alternator feeds a single bus on which all power and lighting loads are connected via circuit breakers. A separate noise-filtered avionics bus can

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Fig. 1 Cessna-210 cockpit circa 1975 with dedicated gauges, 1990s loran and GPS installed in the avionics stack between the pilots (photograph by author).

be switched to the main bus. The alternator continuously charges one or more batteries. The crew can manually select alternator/battery power or battery-only power (in case of alternator failure).

In large aircraft, each engine drives an alternator that generates three-phase power. In older aircraft, a hydromechanical constant-speed drive maintained the alternator at constant speed, generating 115 V at 400 Hz even as the engine speed varied from idle to full power. Multiple ac generators must either be synchronized or the buses isolated from each other during switching. In newer aircraft (Boeing 777, MD-90), the alternator is rigidly connected to the engine so that its speed varies. Rectifier banks and electronics (inverters and converters) convert the variable-frequency ac to 24-V dc and 400-Hz constant-frequency ac. There has been some interest in allowing the distribution frequency to vary, which would complicate the power converters within each electronic device.

There has always been development activity on ac systems at frequencies of 800 Hz and higher to reduce the weight of wiring, motors, and transformers. There have been efforts to raise the amplitude above 28 and 120 V to reduce current in the distribution wiring. In all-electric automobiles and in experimental suspension and engine-valve controls on gasoline automobiles, 350-V dc power is already used. The U.S. F-22 fighter and AH-64 helicopter distribute power at 270 V dc whereas Airbus plans to distribute at 380 V dc on future airliners. Studies have been done for distribution as high as 10,000-V dc. The safety risk to maintenance technicians, crews, and passengers from multihundred-volt power is yet to be understood. Higher voltages will save wire weight but will exacerbate destructive arcing from aged and frayed wires (Sec. III.A).

Each alternator drives main buses to which loads are connected by circuit breakers; the return is via the three-phase neutral in an ac system. A large aircraft will have 2000 electrically powered units, each one requiring a circuit breaker. Safety-critical loads (cabin lights, instruments) are connected to an emergency bus, which is switchable to the ac buses and to a battery that is kept charged by the alternators. Sometimes, essential loads are assigned to multiple buses, such as an "instrument bus" (for safety) and a "radio bus" (for dispatch). Bus interties have been manually switched but are increasingly automated, for example, utilizing software tables that identify the loads required in each mission phase under various failure conditions. Power systems are monitored for under- and overvoltage, under- and overfrequency, current, and temperature. The monitor circuits must themselves be tested periodically at each power-up.

Circuit breakers are usually located in a side panel or overhead panel. The breakers trip automatically after a brief time delay following the onset of excess current. In most aircraft, the breakers can be opened and closed (reset) manually. There is a trend toward locating solid-state breakers remotely (with remote manual engage and disengage) to avoid bringing power wiring onto the flight deck. The result is a saving in wire weight and a reduction in fire hazard. This has been done in many automobile circuits since the late 1980s. Remote circuit breakers (relays) are manually tripped and reset by cockpit switches via dedicated wires or multiplexed data buses. Multiplexing saves relay-control wiring, but introduces the risk that loss of power will disable the multiplexers themselves, thereby preventing operation of the remote relays needed to restore power. Remote relays are often reconfigured by computer according to tables stored in software to put equipment into the proper modes for each flight phase. Automated power moding is especially important in aircraft that lack a flight engineer's station. In 2003, concern escalated about arcs, from wire-to-wire and from wire-to-airframe, that conduct too little current to trip circuit breakers but carry enough energy to ignite fuel oil and fabrics. One solution is to sample the electric current at millisecond rates and look for waveforms that imply arcing. Tripping would then occur when the average current on a wire is excessive or when the waveform implies arcing from damaged or aged insulation. If such circuit breakers mature, they are apt to be required for long-life systems, aircraft, and others.

In most aircraft, ac is distributed to power supplies in each box, where it is stepped up or down, rectified, and filtered. Each box contains a converter that produces 3- or 5-V dc for digital chips, 12- or 15-V dc for analog integrated circuits, 28-V dc for battery chargers, and 400 Hz for synchroexcitation. In newer aircraft, dc is distributed to converters in each electronic box, where it is chopped at 50 kHz or higher, for example, by a triac. The chopped power is stepped down in a small high-frequency transformer, rectified, and filtered to produce power for the chips. Some of the power produced by the converters is regulated between 0.5 and 5% with ripple less than 1%. Efficiency (a measure of internal heat dissipation) varies from 50 to 90% depending on load and design. Switched power supplies radiate at the switching frequency and its harmonics and hence, require shielding. They feed power pulses onto the distribution lines and hence, need input filtering.

Large aircraft carry auxiliary power units (APUs) driven by a small engine that burns kerosene. Some APUs run only on the ground to supply air conditioning, hydraulics, and electricity and to start the engines. Others are rated for in-flight use as an emergency source of power. Aircraft with fewer than four engines sometimes have a deployable wind generator as a source of emergency electric power and hydraulics, for example, DC-10. The twin-engine Boeing 777 has two generators per engine and an in-flight-rated APU. Hence, it is permitted to takeoff with any one generator inoperative.[3] Military aircraft have less power redundancy than airliners.

The Apollo command module was and the Space Shuttle Orbiter is powered by fuel cells that consume hydrogen and oxygen. The International Space Station depends on solar arrays and on batteries during eclipses. Internal electric power is usually distributed at 28-V dc on small spacecraft. The space shuttle generates and distributes power at 120 V, three phase, 400 Hz. Space station power is distributed at 120-V dc. (Early in the design, 440-V distribution at 20 kHz was considered.) The space station produces 80 kW from all four solar panels.

B. Navigation

1. Horizontal Navigation

The Wright brothers did not travel far enough to need navigation. When mail planes became routine and the first daredevils flew the

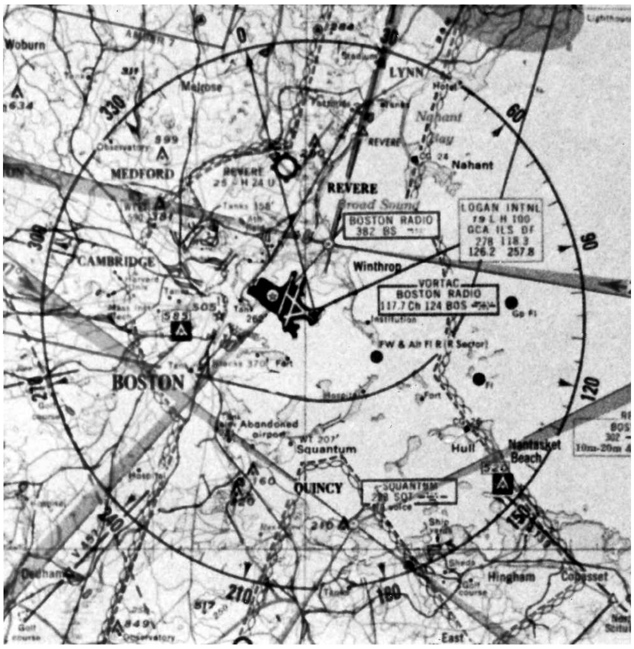

Fig. 2 Four-course airways in the vicinity of Boston, MA, circa 1960 (FAA chart).

Fig. 3 Magnetic flux-gate sensor (courtesy of Humphreys).

Atlantic in the 1920s, the need for navigation aids became apparent. From 1929 to 1948, nondirectional beacons (in the 200–400 KHz band, on 65 channels) were the mainstay of local navigation in several areas of the world (Ref. 4, Chap. 1). Crews could fly toward them, using the magnetic compass to correct for crosswind. The beacons' power output was restricted to a range of 100 miles, thereby not interfering with each other. A few high-power nondirectional beacons worldwide allowed navigation 1000 miles out to sea, for example, in San Francisco and Hawaii. Figure 2 shows the airways surrounding Boston circa 1960, mostly defined by 200–400 kHz radio beacons.

On long flights, crews flew by dead reckoning, measuring airspeed and resolving it into east–north components manually using magnetic-compass heading (Ref. 5, p. 29). By World War I, aircraft had cockpit-mounted alcohol-floated magnetic compasses as heading references; they are still widely used. Figure 3 shows a flux-gate magnetic sensor usually mounted on the fin and reading remotely on the horizontal situation display. Older complex magnetic compasses stored magnetic variation in three-dimensional cams. The cam's output, as a function of latitude and longitude (rotation and axial translation of the cam follower), corrected the measured heading. Modern magnetic compasses are corrected by tables of variation stored as a function of position in the navigation computer. Magnetic compasses are not useful at high magnetic latitudes.

Fig. 4 Air-data sensors on Boeing 737: two pitots, one angle-of-attack, one temperature probe (photograph by author).

Airspeed measurements are needed for flight control and navigation. The Wright brothers did not need to measure airspeed, but their successors installed fluttering tapes and rotating-cup anemometers on their biplanes. In the 1930s, venturi tubes were mounted on aircraft, to be replaced by pitot tubes during World War II. In high-performance aircraft, the air-data computer (Sec. III.D.) computes true airspeed and altitude.

Dead-reckoned position is computed relative to the surveyed airport of departure or along a radio beam (whose overflight is indicated by an audible null). As speeds increased, analog air-data computers derived true airspeed and altitude from static and impact pressure and impact temperature measurements (Ref. 5, Chap. 8). Figure 4 shows a cluster of sensors for pitot-pressure (static and impact), temperature, and angle of attack.

Over oceans, dead-reckoning errors exceeded (often greatly exceeded) 10 n miles. Hence, for long flights, dead reckoning by airspeed and compass was supplemented by celestial navigation (bubble sextant sighted through a side window or through an astrodome atop the aircraft). All of the famous record-breaking flights carried a navigator who was skilled in dead reckoning and celestial navigation.

The VOR is the overland navigation aid for most of the world's aircraft (Ref. 5, Chap. 4.4). There are 1012 stations in the United States alone. In underdeveloped areas and the former Soviet bloc, nondirectional beacons were the norm. Over-ocean, celestial navigation continued in use until loran and Doppler-magnetic-compass systems were introduced in the 1960s (Ref. 5, p. 12 and Chap. 10). At that time, the navigator's station and astrodomes were eliminated on all but long-range military aircraft. When radio aids or visual sightings were used, errors of 1 mile were achievable.

Inertial navigation (Ref. 5, Chap. 7) was introduced into military aircraft in the early 1960s, as a way for interceptors to find their way home in foul weather in Europe and as a way for long-distance bombers to locate their targets within a few miles. (A mapping radar was the terminal sensor.) Inertial navigators evolved from the marine gyrocompass (1905), the naval analog gunfire-control computer (1910s), and the analog aircraft gunsight in the 1940s (Ref. 6). Figure 5 shows the first aircraft inertial navigator, flown cross-country by the Massachusetts Institute of Technology (MIT) Instrumentation Laboratory (now The Charles Stark Draper Laboratory, Inc.) in the late 1950s. It was a huge geometric analog computer resembling an armillary sphere, whose latitude and longitude gimbals were a sidereal drive, like that of a telescope. The size was reduced until triple four-gimbal inertial navigators using digital minicomputers were added to over-ocean airliners in the 1970s, beginning the process of elimination of the human navigators' stations. Triple inertial navigators detect each others' excessive drift and allow the crew to decide which one gives the best estimate of position. They are still used on wide-body jets. Near landfall, the inertial systems are updated by a VOR fix after which the aircraft navigates to its destination on the VOR airways. Figure 6 shows an inertial navigator of the late 1990s with an integral global positioning receiver. The inertial instruments are "strapped-down" to the aircraft, that is, they are no longer angularly isolated in gimbals. Aeronautical Radio, Inc., (ARINC) specifications call the inertial sensor and computer the "inertial reference system," whereas others call them an "inertial navigator."

To correct the inevitable drift of the inertial navigators on long flights, loran was tried at 2 MHz (Ref. 4, Chap. 6) and was relocated to 100 kHz (Ref. 5, Chap. 4.5.1) to achieve greater range. Loran measures the difference in time of arrival of eight-pulse radio clusters from station pairs. The stations are arranged in master–slave "chains." Two or three slaves receive the coded pulses from the master and transmit their own eight-pulse codes. The receiver measures the time delay between receiving the master and slave pulses, thus locating the aircraft on a hyperbola whose foci are the master and slave transmitting antennas. In the 1980s, atomic clocks were installed at all master and slave stations so any station pair could form a hyperbola. The slow cycle time of pulses and the need for a long antenna kept loran from being popular on aircraft. Because of the scanty coverage of the loran chains outside of developed areas, it was supplemented by Omega in the 1970s. Omega was a worldwide navigation aid whose signals were radiated by eight ground-based radio stations near 10 kHz (Ref. 5, Chap. 4.5.2). Omega required continuous, uninterrupted reception from the point of takeoff, hence was a radio dead-reckoning system. It was widely used by corporate jets and several over-ocean airlines but was decommissioned in late 1997. From 1964 to 1996, Transit satellites provided intermittent worldwide fixes to an accuracy of several hundred meters at a fixed location (Ref. 7, Chap. 12.9.2).

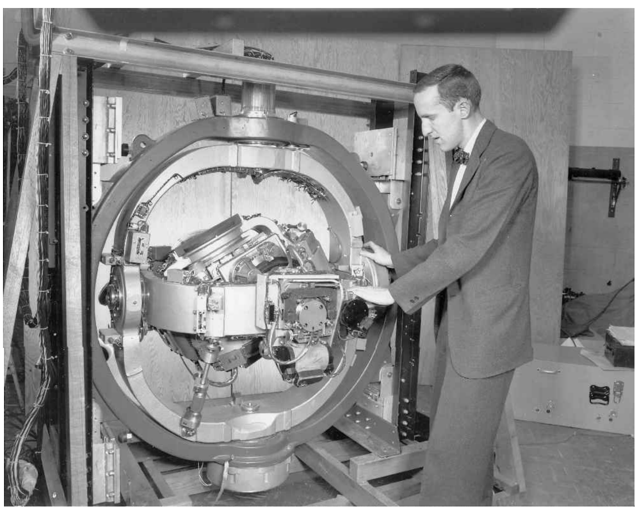

Fig. 5 Spire inertial navigator, circa 1956, five-gimbals; first aircraft inertial navigator (courtesy of The Charles Stark Draper Laboratory).

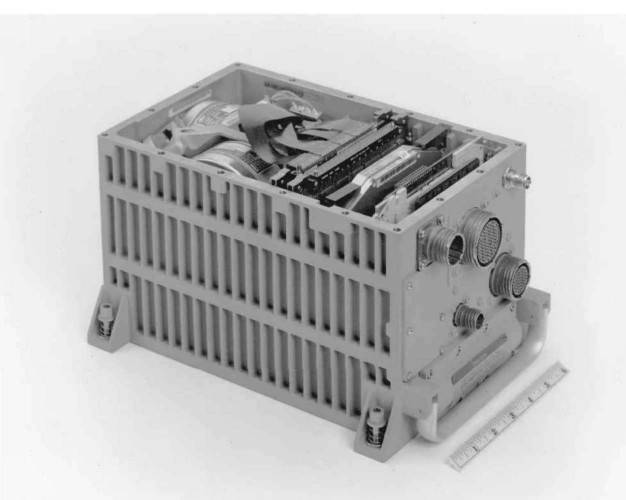

Fig. 6 Strapdown GPS-inertial navigator: tops of two laser gyroscopes visible on left, sensor electronics, input–output, computer, and GPS boards to right, battery behind handle; used on F-18, F-22, and other military aircraft and helicopters (courtesy of Litton Guidance and Control Systems, now Northrop-Grumman Electronics).

Navigation computers must be told their initial position and the waypoints to be followed. These were once entered manually during preflight preparation. At least one commercial accident was attributed to transposition of digits during the manual load. In 2003, navigation data are loaded from a tape, read by a tape reader that is permanently installed onboard (commercial practice), or played into the data bus from outside (military practice). The tapes are prepared by an airline's dispatch department or by military mission-planning staffs. When clearances are changed en route, waypoints were once entered manually but now are selected manually from a menu, either way diverting the crews' attention for a substantial time. Selection of packaged approach and departure procedures alleviates this problem.

In 2003, global positioning system [(GPS), Sec. II.B.3] is becoming the dominant navigation aid for all vehicles: land, sea, air, and low orbit. Several score of manufacturers produce GPS receivers, of which about 10 produce flight-qualified sets [conforming to technical standard orders (TSOs), Sec. III.B]. Two or three manufacturers produce GPS sets for military use that include the encrypters required to obtain full accuracy. Loran is used by ships and general aviation and might become a backup for GPS because their failure modes and atmospheric sensitivities are so different. Loran backup would permit the U.S. military to disrupt GPS deliberately, though at the sacrifice of landing capability because Loran errors are greater than 0.3 n mile (Ref. 5, Chap. 4.5.1). Figure 7 shows a loran ground station; in 2000, an upgrade of loran ground stations was begun, thus assuring service into the first two decades of the third millennium. In 2003, GPS is displacing loran in general aviation in the United States but loran is being discussed as a coarse monitor for GPS, for example, on nonprecision GPS approaches.

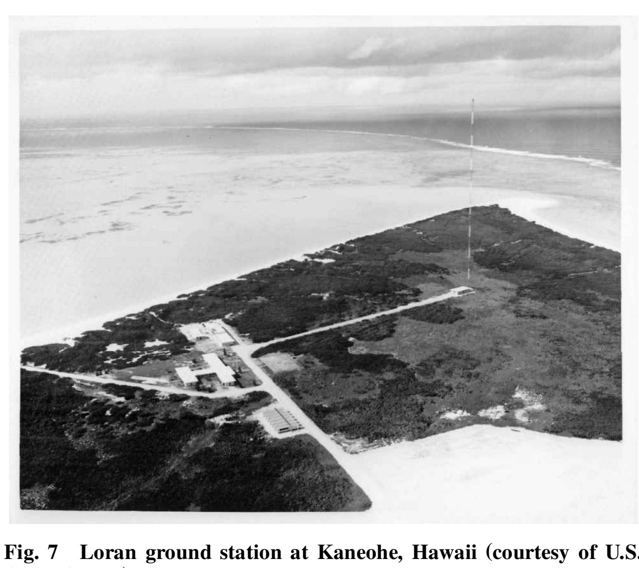

Fig. 7 Loran ground station at Kaneohe, Hawaii (courtesy of U.S. Coast Guard).

Fig. 8 Inertial instruments under test, 1950s: some tables are tilted to place their axis of rotation parallel to the Earth's spin axis; laboratory location is unknown to author.

The earliest inertial instruments and computers were mechanical. Modern angular-rate sensors are laser-based (Ref. 5, Chap. 7) whereas accelerometers are still mechanical. Figure 8 shows inertial instruments under test in the 1960s. The trend is for gyros and accelerometers to be grown on microchips. Micromechanical gyros are vibrating silicon elements whose Coriolis deflection is measured. Micromechanical accelerometers have proof masses whose deflection is measured (in inexpensive instruments), or whose deflection is restored to zero, or whose deflecting elements vibrate, as in the 50-year-old "vibrating string accelerometer" (Ref. 5, p. 322).

Mechanical analog computers began to be replaced by digital minicomputers in the 1960s, using drum and ferrite core memories. In 2003, dedicated inertial-navigation computers use commercial microprocessors and microchip memories (Sec. III.C). Attitude is universally derived from angular pulses processed digitally by quaternion algorithms (Ref. 5, Chap. 7.4.2). The read-out is in heading, pitch, and roll, which are displayed on the attitude-director, horizontal situation display, and head-up display. Initialization of the inertial algorithms is by gravity leveling and gyrocompassing while standing still at a known position and velocity (zero except on an aircraft carrier).

Manual fixes were obtained in military aircraft by placing a cursor on a radar image (Ref. 5, Chap. 11). The most precise images are obtained from synthetic aperture radars that create 1000-ft-long virtual antennas by measuring the velocity of the aircraft precisely for several seconds while synthesizing the image from the Doppler-shifted radar returns. Imprecise velocity measurements defocus the image, which depends on coherence of phase measurements between early and late returns while the aircraft traverses the length of the virtual antenna. In 2003, Doppler-velocity-aided inertial and stellar-aided inertial navigators are used only in specialized military vehicles.

Map matchers were built for military use in updating inertial navigators. The earliest system, automatic terrain recognition and navigation (ATRAN), matched a series of radar images to stored images; it was not deployed. Terrain contour matching (TERCOM) matches stored terrain profiles to observed profiles, as measured by the difference between baroinertial and radar altitude. TERCOM has been deployed on cruise missiles. It updates position over selected patches of rough terrain, where a unique match can be found (Ref. 5, Chap. 2.6).

Naval aircraft must locate moving carriers at sea. In the 1950s, the U.S. Navy sponsored tactical air navigation (TACAN), which modulated the amplitude of distance measuring equipment (DME) pulses at L band (960–1215 MHz). The resulting receivers were lighter and more expensive than VOR receivers but no more accurate (Ref. 5, Chap. 4.4.7).

2. *Vertical Navigation*

Vertical navigation has long been based on barometric altimetry used in conjunction with a standard profile of pressure vs altitude. Barometric altimetry is, therefore, not a precise measure of altitude in an atmosphere that does not match the standard. However, it is a good way to separate aircraft vertically along an airway because all aircraft measure the same pressure. Barometric measurements have 1-s lags due to the flow of air into and out of the tubing that connects the pitot-static ports to the transducer. Hence, the vertical accelerometer of an inertial system was mixed with barodata to give smoothed altitude rate (Ref. 5, p. 374). This is particularly valuable to military users who need vertical velocity for bombing and for terrain updates. Radar altimeters are used for terrain clearance and landing, for example, to control the flare.

Altimetry errors increase with altitude because the rate of change of pressure with respect to altitude decreases exponentially. Below 29,000 ft, civil aircraft are separated in 1000-ft layers. Above 29,000 ft, separation was 2000 ft everywhere until 1997 when spacing was reduced to 1000 ft over the North Atlantic on certain airways. Separation over Australia and other ocean areas was reduced. In 2002, separation was reduced to 1000 ft over northern Europe below 41,000 ft. In 2005, the United States will probably adopt the same reduced separation. Reduced separation requires specially calibrated pressure probes and air data computers. Supersonic aircraft are separated by 4000 ft above 45,000-ft altitude.

3. *Airway Navigation*

In 2003, overland air navigation throughout the world continued to be on VOR-defined airways (Ref. 5, pp. 41, 646). China and the former Soviet Union are installing VORs at entry corridors and in their interiors. Meantime, the GPS, at 1.2 and 1.6 GHz (Ref. 5, Chap. 5.5 and Refs. 8 and 9) is becoming the mainstay of navigation as methods of detecting satellite outages and receiver errors are found. It has been adopted by India for in-country navigation.

Figure 9 shows one of the block IIF spacecraft that emit the navigation signals and that will be launched in the first decade of the 21st century. Over land, it is expected that the wide area augmentation system (WAAS) will replace VOR as the navigation aid defining airways and a sole means of navigation in the first decade of the 2000s. WAAS is a network of ground stations, each of which has several fixed GPS receivers that transmit the measured GPS errors to nearby aircraft (directly on vhf radio, via satellite, or via mode-S radio link from existing surveillance radars). En route aircraft can thereby correct their own GPS-derived positions to achieve 10-m errors in-flight. It is possible that WAAS systems in some countries will be privately owned and collect fees from users. The technique of measuring GPS errors at a fixed station and broadcasting them to nearby vehicles is called differential GPS (DGPS). In the United States, the Federal Aviation Administration's (FAA's) WAAS will be separate from the Coast Guard's marine and land DGPS systems that broadcast corrections on medium frequencies.

For most of GPS's history, the U.S. government has deliberately corrupted the GPS clock (Ref. 5, pp. 198, 235; Ref. 8), further increasing navigation errors. In 2000, this "selective availability"

Fig. 9 GPS block IIF spacecraft (courtesy of The Boeing Company).

was eliminated. However, civil air operators in all countries fear that during a war, which might not even concern their countries, the United States will again corrupt the GPS clock. Hence, the European Union is slowly developing its own WAAS (called Galileo, EGNOS, or GNSS) which may use GPS, Glonass, geosynchronous satellites, and DME for fault tolerance. In November 2002, only 7 working Glonass satellites were in orbit, of the 24-satellite constellation, thus giving intermittent coverage. If the Galileo signals in space are the same as GPS's, the world will have a unified navigation system.

The United States may begin to decommission its 1012 VORs in 2005 and may terminate service in the 2010s except for a small number of stations that define key airways.[10,11] GPS-aided inertial systems are slowly becoming the mainstay of navigation over oceans and in undeveloped areas. Section III.G describes air traffic control in developed and undeveloped areas.

To many practitioners, navigation is the determination of the state vector (position and velocity) whereas guidance is the steering of the aircraft based on navigation data. To other practitioners, for example, ARINC specifications, navigation includes the state vector determination and steering process: hence, the navigation computer and flight management computer are the same.

C. Communication

The Wright brothers communicated by shouting over the din of their engine. Now communication in an aircraft consists of an internal intercom and external radio links for voice and data. The first recorded use of a radio on an aircraft was in 1912 over New York City when a pilot used a wide-bandwidth spark-gap transmitter to send Morse code messages to a ground station. During World War I, airborne spotters sent Morse code messages to correct artillery fire.

For decades, external links were via high-frequency radio (in the 30–300 MHz band) by Morse code or voice. Static caused by worldwide lightning is the principal source of hf noise. VHF (near 100 MHz) radio was introduced after World War II in the west for overland use via a network of line-of-sight unattended radio stations. The frequency band from 118 to 127 MHz was reserved exclusively for civil aeronautical use. However, hf radio remained the usual over-ocean means of communication until satellites became available in the 1990s. Even in 2003, hf is more widely used than satellites. Some aircraft carry steerable antennas, for example, the International Maritime Satellite (INMARSAT) Aero-H, that track geosynchronous communication satellites (comsats).

In the 1970s, the vhf band was extended to 760 channels at 118–137 MHz, spaced 25-kHz apart. At the beginning of the 21st century, the spacing may be reduced further, first in Europe. The U.S. aeronautical network costs more than 1 billion dollars per year to maintain and upgrade, for example, maintaining relay stations and leasing telephone lines to traffic control centers. Military aircraft carry uhf (225–400 MHz) radios that incorporate encryption devices. In the 1990s, aeronautical comsats became available to relay voice and data between land stations and aircraft. INMARSAT operates four geosynchronous spacecraft that relay marine and aeronautical messages at L band for more than U.S. $10/min. They are used for "company radio" but may be extended into traffic control. Many new aeronautical communication services are in development, mostly using satellites that are at low enough altitude to work with recessed slot antennas. Competition will undoubtedly reduce per-minute costs.

Communication at international airports is supposed to be in English so that every pilot can understand instructions sent to every other pilot, for safety reasons. There has been an increasing number of accidents caused by misunderstanding of traffic control instructions spoken among non-English-speaking controllers and non-English-speaking pilots. Aeronautical-English courses are given regularly to reduce the problem. Wise traffic controllers speak slowly and with limited vocabulary to crews who seem to lack English language skills. Data-linked traffic instructions will initially be in English but might be translated automatically to the language of the crew.

The International Civil Aviation Organization (ICAO) defined a mode-S modulation on surveillance radar (interrogation at 1030 MHZ and replies at 1090 MHz) that allows the ground and aircraft to exchange information at low data rates (1200 bps) and allows the ground to send data to specific aircraft (addressed by transponder code). When it began, mode-S was called the discrete address beacon system. Mode-S is used air-to-air by onboard collision-avoidance devices [Traffic Alert and Collision Avoidance Systems (TCAS), Sec. II.E] and may, in the future, disseminate differential GPS corrections.

In North America, ARINC (jointly owned by the airlines) operates a vhf company radio data link, ARINC communication addressing and reporting system (ACARS), via about 200 ground stations. In the United States, ACARS carries dispatch, repair, preflight clearances, and gate information; in Canada, flight clearances are delivered by ACARS. ACARS transmits data as well as voice. Other communication systems are being developed to transmit voice, data, fax, and email between company dispatchers and aircraft. Experiments are transmitting air-traffic control displays and weather displays to aircraft, an idea first suggested in the 1950s (Ref. 4). Links will be via transceivers in the gate area of an airport and via satellite in flight.

D. Flight Control

The earliest aircraft, in the late 19th century, were hang gliders, stabilized by shifting the pilot's body weight. The Wright brothers added an elevator lever and wing-warp roll/yaw coupled control by shifting their bodies laterally.[12] In 1908, Glenn Curtiss added primitive ailerons and decoupled the roll and yaw controls. By 1910, Bleriot and Farman introduced the stick and rudder pedal as the primary flight controls.

Pilots of early aircraft flew by hand using rudder pedals and a stick or control column (fly-by-cable). The controls were connected to the rudders, ailerons, elevators, and flaps by wire rope or rigid linkages. In large aircraft, the stick/column was connected to aerodynamic tabs that deflected the control surfaces, resulting in amplified forces but sluggish response. Control tabs continue in use on the B-52, Boeing 707, DC-8, and DC-9, for example. Trim wheels reduce the pilot's muscular force in level flight by holding the tabs at a fixed angle.[1] Throttles were connected to carburetors by spring-loaded wire rope, as in automobiles.

Before World War II, primitive pneumatic autopilots (powered by manifold vacuum) held the wings level and, sometimes, held the fuselage level. The pilot made turns and maintained speed manually. Climbs and descents were manual. The control authority was less than 25% of the force that a pilot could apply, to ensure that the pilot could always overpower a defective autopilot. Elmer Sperry demonstrated a pneumatic autopilot in 1913 on a flying boat.[1] During World War II, some bombers had vacuum-tube autopilots to stabilize the aircraft during bomb runs and to reduce pilot fatigue during long missions.

In the 1950s, some aircraft became so heavy or flew so fast that hydraulic boost was required to move their control surfaces. At first, the hydraulics assisted the direct cable connection to the control surface. As aircraft grew in weight, pure fly-by-oil arose, in which the wire rope from the control column pulls a hydraulic valve, not the control surface itself. The X-15 research aircraft was one of the first of these. In the late 1940s, the rocket-powered X-1 found that flight controls could become ineffective at transonic speeds. In the late 1950s, the "century series" of military supersonic fighters and, in the late 1960s, the Concorde supersonic transport required stability augmentation, which was done with analog electronics that inserted low-authority signals into electrohydraulic actuators. In 2003, almost all jet aircraft employ analog yaw dampers, which are stability augmenters that can be turned off at the cost of extra pilot workload. The earliest yaw dampers were on the U.S. B-47 and B-49 bombers circa 1946 (Ref. 1). Figure 10 shows an electrohydraulic actuator for a yaw damper. Figure 11 shows a single-axis rate gyroscope and single-axis accelerometer for an aircraft flight stabilization system.

In the late 1940s, hydraulic motors were introduced as the sole means of moving the pitch trim and flaps slowly. The C-5 cargo transport has dual-hydraulic trim motors, each powered from a separate switch and separate hydraulic system. Electric actuation, called fly-by-wire, was not introduced until the Gemini spacecraft's reaction-control jets in the mid-1960s. The first aircraft fly-by-wire system was the F-16's quadruply redundant analog flight controls in the mid-1970s. The space shuttle (1977), French Mirage fighter

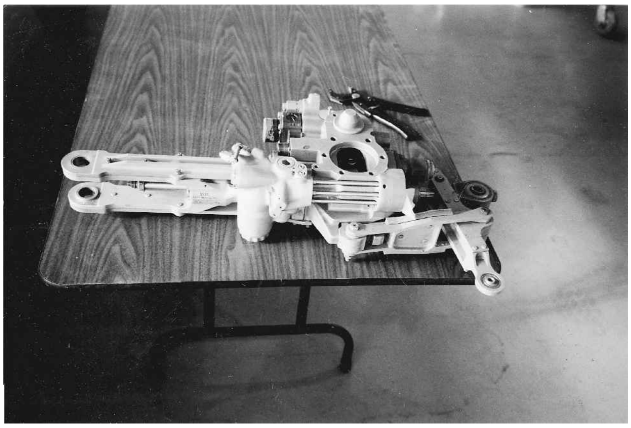

Fig. 10 Boeing 737 rudder actuator, electrically operated, hydraulically powered (photograph by author).

Fig. 11 Single-axis flight-control gyroscope and accelerometer, 1960s [courtesy of Sperry Flight Systems (now Honeywell, Inc.)].

(1980), and Swedish Grippen fighter (1988) employ fly-by-wire without cable backups. In a fully fly-by-wire system, the control column or hand controller sends electrical signals to a computer that operates the control surfaces (or spacecraft's reaction jets). Where there is no backup mechanical system, the fly-by-wire system has redundant electric power supplies, redundant sensors, and fault-tolerant (perhaps redundant) actuators. Backup modes accommodate failures of sensors, actuators, and computers.

Most fly-by-wire aircraft in 2003 have mechanical cable secondary control systems that have poor handling qualities but allow safe flight. The Airbus 320 series has pure fly-by-wire in pitch-elevator and in roll with mechanical cables in pitch-trim and in rudder. Dual pilot–copilot hand-controllers require a method of overriding a failed unit. Full deflection of one controller can be interpreted by the flight control computers as a signal to ignore the other. The author believes that two-hand-controller logic is still not worked out.

Even with electronic redundancy, the weight of a fly-by-wire system on a large aircraft is lower than that of an all-mechanical system with its wire ropes, pulleys, guides, temperature compensation, and force feedback. Data do not yet exist that compare the reliability of fly-by-wire with that of an equivalent mechanical system. Electronic redundancy has been architected in many ways, as explained in Sec. III.E.

Most fly-by-oil actuators are of two types. Those used with split control surfaces accept a single control input, the voting being done by the deflection of the control surfaces. (A failed actuator or control channel moves one surface differently than the others.) Those used with a single control surface have multiple control inputs, internal voting, and multiple hydraulic drives. During the past 20 years, distributed hydraulic systems have been tested in which each electrically powered actuator contains one or more small hydraulic pumps, thus avoiding long runs of hose to and from central reservoirs. Even more radical are plans for all-electric airplanes in which the actuators are electrical, thus avoiding hydraulics entirely. To the author's knowledge, there are no such systems in operation on manned aircraft. Electric pitch trim is common in civil airliners and military aircraft.

A fly-by-oil or fly-by-wire system needs artificial "feel" feedback to the stick, hand controller, and rudder pedals. The earliest feel systems used springs. Newer feel systems are servos, actuated by signals proportional to measured dynamic pressure and trim angle. (They may contain springs.)

Modern large civil jet engines produce thrust-by-wire, beginning with the Boeing 757. The throttles send signals to a full-authority digital engine computer (FADEC) that adjusts the fuel flow, damper doors, nozzles, inlet cones, and other engine actuators required to generate efficient, quiet thrust. The FADEC computer is part of the engine, cooled by engine air, and driven by crew-operated throttles and the flight-management computer. The B-2, having no rudder, controls yaw by differential thrust. Test have been made using differential thrust for yaw control of civil aircraft, in case of a hydraulic outage. (Hiram Maxim proposed differential thrust control about 1900.) Pitch trim is routinely adjusted by pumping fuel fore and aft, manually or automatically. Baffles in the tanks reduce the oscillations caused by sloshing.[13]

At near-sonic speeds, the wings and control surfaces deform, shock waves form, and the airplane's stability properties change, even leading to control reversals (Ref. 1, Chap. 19). The flight control system is able to maintain stability by altering the algorithms. The nonlinearities of high-speed flight are discussed in Ref. 14. Vibrations (below 100 Hz) due to aeroelasticity are called flutter. It has been an engineer's dream to sense the vibration in real-time and eliminate the flutter. Thin-film sensors are said to be available in 15-kHz bandwidth.

The flight control computers receive inputs from a digital air-data computer that derives static pressure, dynamic pressure, airspeed, outside air temperature, angle of attack, and angle of sideslip from pressure and temperature measurements (Ref. 5, Chap. 3.4.3 and Chap. 8). The flight control computers also receive inputs from an autopilot that permits handsoff straight and level flight, turns, climbs, descents, approaches, and even landings. The more complex autopilots couple attitude control with thrust control to achieve four-dimensional navigation (Sec. III.G). The space shuttle has deployable air-data probes for use below Mach 4.

The debate still rages as to whether fly-by-wire flight controls should incorporate envelope protection that prevents a crew from exceeding preselected limits, usually acceleration and angle-of-attack limits. In civil aircraft, envelope protection is provided in Airbus aircraft but not in Boeing aircraft. In military aircraft, crewmen who are trained to fly near the limits of the airframe are allowed to exceed them, accepting a damaged aircraft rather than be downed by enemy action. Some argue that civil pilots should also be able to exceed limits to save an aircraft from unforecast extreme situations.

Hardware and software are developed using an "iron bird" simulator, a test rig that duplicates the flight actuators, hydraulic lines, and the forces on control surfaces. Analytically simulated sensors or live sensors on rotating platforms are included. The iron bird verifies the detailed functioning of hardware and software (Sec. III.D.2). Flight experiments are sometimes made with a variable-stability aircraft (Sec. III.D.2), so that details of the control algorithms and crew interface can be tested before the design aircraft is built. Flying-qualities specifications, for example, Cooper ratings (see Ref. 15), exist that combine the test pilot's subjective opinion with the objective characteristics of the oscillations of the aircraft. Ratings cover level flight, crosswind landings, turbulence, high angles of attack, and other flight conditions.

E. Onboard Collision Avoidance

In the 1980s, onboard equipment became available to predict air-to-air collisions and recommend maneuvers. Traffic alert and collision-avoidance systems (TCAS) interrogate nearby aircraft to measure range using traffic-controllike pulses (transponder mode-S). In Europe, TCAS are called airborne collision avoidance systems (ACAS). Advanced TCAS sets have directional antennas that measure the approximate azimuths of other aircraft and display them on the horizontal situation display (HSD). In a multiaircraft encounter, the aircraft must exchange data (on the mode-S link) to ensure that the maneuvers do not conflict (Ref. 5, pp. 684–686; Ref. 16). Software upgrades for TCAS, developed by Mitre Corporation, continue to reduce false alarms and improve multiaircraft avoidance maneuvers.[17] In 2002, version 7 for TCAS will reverse the resolution advisory if the other aircraft maneuvers improperly.

In the late 1990s, tests were conducted with aircraft that broadcast their measured position (by whatever means but usually GPS) and displayed the positions of nearby aircraft on its HSD or weather radar. Terrain, storms, icing, shear, and nearby aircraft could be shown on the same cluttered display in each cockpit. It is not clear, in 2003, how such automatic dependent surveillance (ADS-B, for "broadcast") systems will interact with TCAS and with the ground-based traffic control system. In January 2001, the first near miss (about 100 m) occurred in Japan due to conflicting instructions from a TCAS and ground controller. In 2002, the first midair collision occurred in southeast Germany due to conflicting instructions by a TCAS and a ground controller. Two aircraft were crossing at the same assigned altitude over a VOR (possibly poor European flow control in assigning altitudes). The TCAS on the Boeing 757 issued a fly down advisory while the ground controller told a Tu-154 to "descend immediately." They collided while both were descending to avoid collision, killing all aboard both aircraft. It seems essential that onboard advisories (especially when other nearby aircraft have no TCAS or ADS-B) be transmitted to the ground to guide ground controllers in issuing instructions to unequipped aircraft.

Since the 1960s, ground proximity warning systems, which are radar altimeters, alerted the crew when the aircraft descended below a preset height above terrain, in an effort to reduce the incidence of "controlled flight into terrain." In the 1990s, newer equipment became available. Based on measured position, the terrain awareness warning system (sold under trade names such as EGPWS) consults a digital terrain database (stored in 5-n mile squares and as fine as 0.25 n miles in mountainous areas near airports) and compares to barometric altitude. An alert is sounded if the present or forward-projected clearance is too low, or if the aircraft is descending too quickly for its altitude. It alerts much earlier than a radar altimeter. Such a system is described in Ref. 18.

Some military aircraft fly close to the ground to avoid enemy radars, and some fly in formation. These avionics are discussed in Ref. 5, Chaps. 1.8 and 11.6.

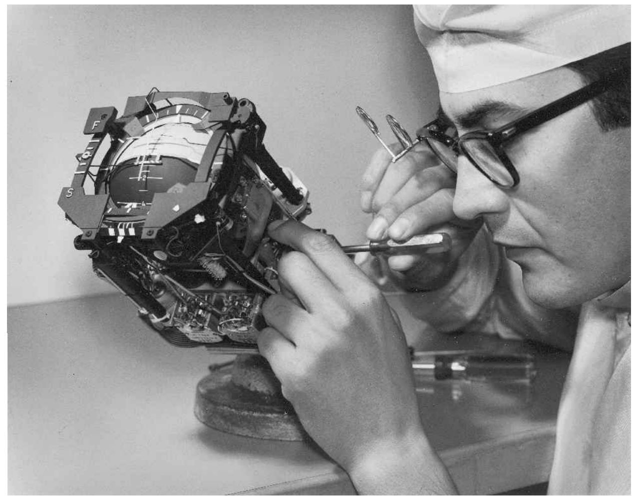

Fig. 12 Mechanical flight-director indicator, shows attitude and steering errors [courtesy of Sperry Flight Systems (now Honeywell, Inc.)].

Fig. 13 MD-11 cockpit with multifunction displays and controls [courtesy of McDonnell Douglas Company (now The Boeing Company)].

F. Cockpit

By the end of World War II, the basic displays and the T configuration on the instrument panel had evolved. The vertical gyroscope was in the center, the directional gyro below, and the altimeter and airspeed indicator on each side. Crews operated the aircraft with a stick or control column, rudder pedals, throttles, switches, dials, and fuses. Barometers were replaced by precision barometric altimeters that had a setting for sea-level pressure. The turn-and-bank indicator (combined yaw rate gyro and lateral accelerometer) and magnetic compass completed the basic instrument panel by the late 1930s. Many aircraft had a radio-magnetic indicator that showed a plan view of the aircraft's magnetic heading and directions to radio stations. Long-range aircraft had a navigator's station at which a plotting board and astrodome were located. Radium-lit dials allowed night flights when no electric power was available. By the late 1970s, the vertical gyroscope was being supplemented, on complex aircraft, by the flight director, also called an "8-ball," (Fig. 12) whose attitude indications came from a remote inertial navigator.

The increasing complexity of avionics made dedicated subsystem display panels obsolete and forced the installation of multipurpose cathode-ray tube (CRT) displays beginning in the 1970s (Fig. 13). In each phase of flight, the crew sees different displays, the circumferential buttons have different labels, and the subsystems are in different modes. Failures are annunciated, sometimes with recommended actions. In 2003, new aircraft have flat-panel displays (usually arrays of liquid crystals), color-coded to show classes of information and to identify critical failures. They are driven by redundant symbol generators, sometimes packaged separately from the display. The extent of pilot overrides of automatic actions is still an open issue. North American manufacturers tend to alert the crew and leave the choice of actions to them; European manufacturers tend to preprogram contingencies and take automatic actions. Simulation and flight experience will refine the extent of intervention in the 2000s.

In the 1970s, optical map presentations were superimposed on video symbology. These electrooptical devices were so expensive that few, if any, went into production. In 2003, all map displays are electronic. The HSD and vertical situation display (VSD) are either CRTs or, increasingly, flat liquid-crystal panels. Their pictorial representation emulates the earlier generation of analog displays (Ref. 5, Chap. 15.3). Figure 13 shows a cockpit with HSDs, VSDs, and status displays, often called a "glass cockpit" in the aggregate. Weather radars historically had their own displays, but, in the newest aircraft, weather is superimposed on the HSD along with nearby traffic and terrain heights. Turbulence, microbursts, wind-shear, and ice pictorials will be added with appropriate switches to declutter the display.

Hand controllers are replacing the stick and control column in fly-by-wire aircraft. Servofeedback adds appropriate feel, depending on computed aerodynamic pressure on the control surfaces. In single-pilot military aircraft, the hand controllers are covered with buttons, often one per finger, to allow rapid actions without removing one's hands from the controls. The buttons are for radio controls, autopilot engage, trim, and missile launch, for example. Civil aircraft have several buttons on the control wheel or hand controller.

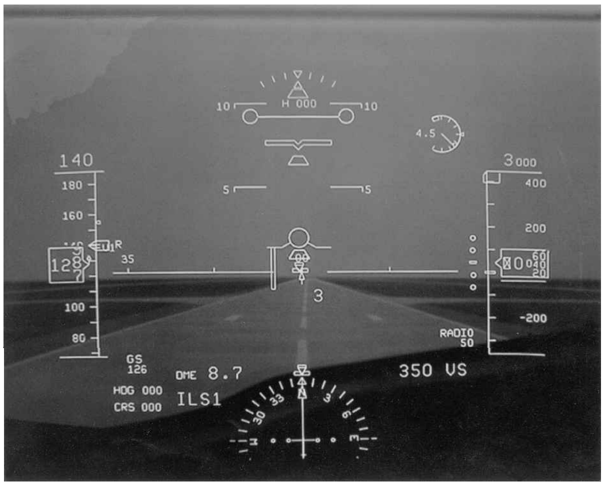

Fig. 14 HUD configured for takeoff, shows heading, airspeed, altitude, pitch, and other data (courtesy of Rockwell Collins Flight Dynamics).

Head-up displays (HUD) were invented in the 1960s for gunfire control and for low-visibility landing in northwest Europe. They were little used in civil aviation until the 1990s, when they were installed in SwissAir, Alaska Airlines, Federal Express, and Southwest Airlines aircraft. Figure 14 shows the view through an HUD whose symbology is focused at infinity; such HUDs qualify aircraft for Category II landing. HUDs with many more symbols are widely used in military fighters for steering toward targets and aiming guns and missiles with the computed lead angle. The Space Shuttle Orbiter's HUDs are key displays during the power-off landing, although crews are trained to land with the HUD failed.

Synthesized voice alarms have been in use for 10 years. A "speak" button enables a computer to recognize a limited vocabulary of commands, thus reducing crew workload. Centralized alarm systems scan engine data and electronic built-in-test circuits (Sec. III.E) displaying faults on multifunction status screens.

For 50 years, pilots boarded aircraft with a briefcase full of charts, checklists, and emergency procedures while flight engineers boarded with subsystem user manuals. Beginning in the late 1980s, these began to be stored digitally and displayed on multifunction displays. In 2002, Boeing announced an "electronic flight bag" that uses a dedicated flat screen in the cockpit. Also in 2002, the FAA issued guidelines for electronic flight bags. The guidelines cover portable and permanently installed computers. Electric power, data, and radiation interfaces are defined. The guidelines prohibit the use of portable computers as the sole source of data. In 2003, crews still carry hard copies; in another decade, many will not.

Simulators are needed to design the cockpit layout, to place instruments, to design the controls, switches and keypads, and to create a subsystem management policy. High-fidelity simulators are needed for economical crew training. The venerable Link trainer (patented 1929) taught three generations of students to fly on instruments. It was a fully enclosed tiny cab mounted on a pivot that would tip over without active control. The cab had a full set of instruments driven by an analog computer. The pilot's stick movements kept the cab level, pitched, or rolled by driving two pneumatic bellows in pitch and two in roll. (Link's father was an organ maker.) An analog pen recorder showed the computed ground track. If you could fly a Link trainer, you could fly any light aircraft. In the 1990s, level-D simulators (terminology of the U.S. and European aviation authorities) have trained pilots to fly in the copilot's seat in revenue service without previously having flown the real aircraft. The level-D cab is mounted on six hydraulic rams that give it six degrees of freedom in a cube about 2 m on each side. The cab includes the pilot, instructor, simulated cockpit, instructor station, and a projector that displays external scenery, often more than 200-deg wide. These simulators are driven by several digital computers that execute the aerodynamic equations for each aircraft type and generate realistic, projected visual displays of selected airport areas. Part-task computer-based trainers are becoming ever more important in drilling crews on the logic and menus of inertial navigators, GPS sets, autopilots, and flight management systems. Military training simulators emphasize radars, weapon management, and electronic warfare. The advances in the cockpits of fighter aircraft are described in Ref. 19.

During and after World War II, long-range aircraft, civil and military, carried two pilots, a flight engineer, and a navigator. As a result of automated navigation and subsystem management, aircraft of the 1990s require only two crew stations, although, on flights longer than 8 h, three or four pilots are often aboard to allow for rest. Will aircraft someday be pilotless as are intraairport rail cars, Metro rail lines in Paris and Toulouse, and elevators?

The onboard cockpit of a manned spacecraft resembles that of an aircraft 10 years older because risks and low-production volumes discourage use of the latest technologies. That was true of Apollo and is also true of the Space Shuttle Orbiter and the International Space Station. In 2003, the orbiters are being upgraded, one-by-one, to glass cockpits. By 2004, all orbiters will have 11 flat-panel displays. The design of manned spacecraft cockpits makes heavy use of developmental simulators because so much of it is being built for the first time.

G. Passenger Services

The only passengers carried by the Wright brothers were student pilots (in late models, circa 1908). The Wrights would have been astonished at electronic services for passengers. Since at least World-War II, electrical intercoms have been installed in civil and military passenger aircraft to allow flight crews to make announcements (often unintelligible) and talk to the cabin crew. Cabin crews can respond to passenger annunciations for service by observing an indicator light over the seat. These features required wiring at each seat. In the 1970s, multiplexed audio was added at each seat to provide taped music, news, and comedy programs and, on some airlines, to allow passengers to listen to air-traffic-control conversations. Movies were added as were video product advertisements and taped safety messages. In some aircraft, movie film traveled the length of the cabin, reaching several mechanical projectors en route. Audio was multiplexed to all of the seats. A transducer in the seat arm drove a pneumatic headset (like an old-fashioned stethoscope), which is still ubiquitous at the centenary of the Wright brothers.

The entertainment part of the cabin electronic is often referred to as in-flight entertainment (IFE). A typical system consists of redundant head-end servers driving demultiplexers in each bank of seats via copper wire. (Radio links are much discussed to reduce wiring.) Passengers signal the head end as to what they want to see or hear. The head end may connect to antennas for satellite television, satellite voice, or ground cell phones. The head end includes a data loader, which often stores several weeks of programming, films, advertisements, and announcements in several languages. Each manufacturer has its own loading medium and formats, usually on tape or CD-ROM. The film industry expects to load directly to each aircraft via satellite, as they will to stationary movie theaters, thus saving the cost of masters and reducing piracy.

Corporate jets sometimes provide satellite television and video games for pampered passengers. Some airlines experimented with forward-looking video cameras, for example, mounted in the wheel well or on the upper fin. (These also allow the flight crew to observe the configuration of flaps and speed brakes, but not of slats.)

In the 1990s, telephone (via cell or satellite) and route-of-flight displays were added. In the 2000s, gambling, video games, computer battery charging (if the risk of explosion of lithium batteries is acceptable), rental computers, a central printer, internet, and local television are becoming available, displayed on flat screens at each seat. Airlines will match their services to the cultural preferences of their passengers: Europeans seem to demand news and sports whereas Asians want gambling.

Noise-canceling headsets became available in the late 1990s, measuring the actual sound pressure within the headset and comparing it with the electronic input to the headset. A milliwatt amplifier creates whatever artificial noise is needed to drive the difference to zero, thus canceling the acoustic noise. Alternatively, the low-frequency noise level can be measured outside the headset, and an amplifier can cancel the sound inside. In either case, passengers can listen to voice or music with background noise suppressed more than 10 dB or can simply wear the headset to cancel ambient noise while sleeping. The big obstacle is cost: Noise-canceling headsets cost more than U.S. $100, whereas the usual pneumatic headset costs less than a dollar. Investment and theft are likely to be the deciding factors; perhaps first-class and business-jet passengers will be the first to be offered this service. Designers must avoid the possibility of ear damage caused by amplifier failures.

A further step to noise reduction would be a distributed array of microphones throughout the cabin that measure ambient noise and a computer that would calculate the sound field at each of several distributed loudspeakers that would emit sound at the computed frequencies, out of phase to cancel the noise at its location. This would produce quiet zones in the aircraft whose size increases as the number of loudspeakers increases. The major disadvantage is the large amount of electric power needed if quiet zones are to extend over most of the cabin.

After the terrorist attack on the United States in 2001, security became a larger issue, demanding cabin video surveillance from the cockpit and a fault-tolerant data bus with video and crew audio, separate from the entertainment system.

In the 1990s, passenger service equipment seemed to be handmade, bulky, and subject to frequent failure. In the 2000s, major avionics companies were entering the market thereby raising the quality of equipment provided by a turnkey vendor. The large avionics monopolies have the world-wide repair facilities to service IFE and have a large enough production volume to make their equipment reliable and cleverly designed, albeit at high cost. Airlines will probably profit from the sale of some entertainment services, for example, pay television, internet access, and gambling, as they do from the sale of alcohol.

III. Avionic System

A. Installation

Figure 15 shows the installation of avionics in a large multipurpose aircraft. Antennas on the top, bottom, and nose receive and transmit radio signals at all attitudes. Coaxial cables transmit the antenna outputs to the avionics bay. A weather radar or military fire-control radar is placed in a plastic radome at the nose. Air-data sensors on the nose (Fig. 4) either have local electrical transducers or, more commonly, connect to transducers in the avionics bay via pneumatic tubing. The avionics bay is sometimes placed directly behind the nose, simplifying the radar wiring and pneumatic tubing. In other aircraft, the nosewheel is located as far forward as possible, thus moving the avionics bay aft and complicating the radar wiring and air-data tubing. Power wiring is fed to the avionics bay from the generators via appropriate circuit breakers. Electronics in the avionics bay are cooled, most often by conditioned air, occasionally in military aircraft by water-cooled cold plates. The signals generated in the avionics bay are delivered to 1) cockpit instruments, 2) control-surface actuators (almost always electrohydraulic), 3) tail-mounted recorders, and 4) antennas, as signals to be radiated.

Critical signal and power wiring must be routed by diverse redundant paths to reduce the likelihood that chemical fires, mechanical damage, explosions, or gunfire will disable the aircraft. All subsystems must survive extreme environments nonoperating but only flight-critical subsystems need operate in case of cooling system failure. Military fighters have external mounting racks (internal racks in some stealth fighters) to which power and signal wiring is supplied. Missiles, fuel tanks, or pods attach to the racks.

Aircraft wiring consists of power cables (16 gauge or thicker, protected by circuit breakers), signal wires (once also 16 gauge, now fragile 22 gauge or thicker), and coaxial cable (from antennas). Wires are rated by current-carrying capacity at a maximum temperature and by the breakdown voltage of the insulation. Wires are bundled in harnesses or ribbons, often shielded as shown in Fig. 16.

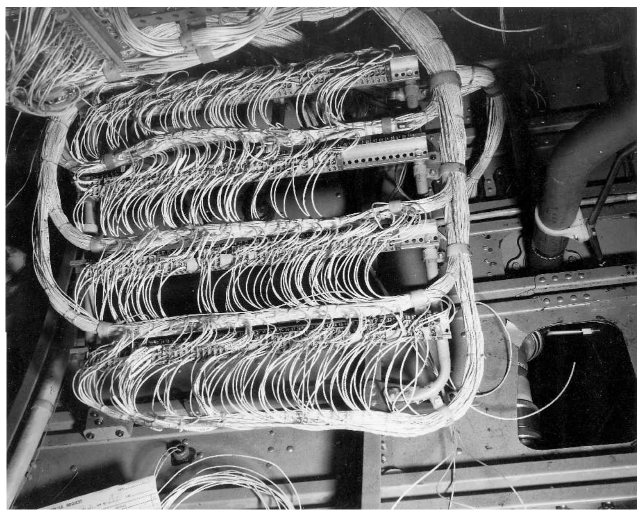

Fig. 16 Wire bundles in DC-8 airliner in 1970s (courtesy of McDonnell Douglas Company, now The Boeing Company).

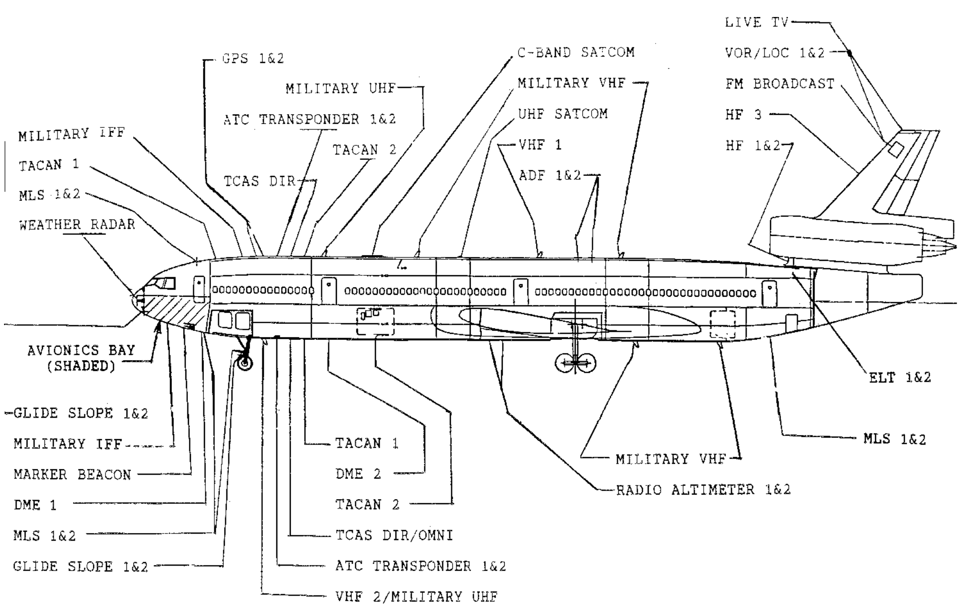

Fig. 15 Antenna farm and avionics bay on multipurpose aircraft: note placement of redundant antennas [courtesy of McDonnell Douglas Company (now The Boeing Company)].

Wires are color coded and printed with identification numbers keyed to schematic diagrams to aid debugging. In the past, a single wire has been run from origin to destination but there is interest in providing intermediate connectors so sections of cable can be replaced without splicing (at a cost in reliability). Designers have been concerned with chafing, vibration, overheating, perforation of insulation due to overvoltage, and chemical damage, for example, from fuel, hydraulic oil, and toilet residue. Insulation must self-extinguish when burned vertically or horizontally while emitting minimum amounts of toxic gases. Several airliner crashes have been attributed to chafed wiring.[20,21] Some multiplexed aircraft use fiberoptic signal cable, especially when the airframe contains large amounts of nonmetallic composite materials that do not shield lightning and man-made radiation. An unperforated metal aircraft would act as a Faraday cage, whose internal electric field was independent of the external field. A real aircraft has windows, antenna perforations, and other apertures that allow the electric field to enter. Wire runs for non-safety, non-mission-critical functions can be replaced by internal radio transmissions, for example, in security sensors, fire alarms, and entertainment systems.

ARINC standards exist for rack sizes, cooling, and connectors on commercial aircraft [see commercial aeronautical standards produced by the International Civil Aviation Organization (ICAO), Montreal; ARINC, Annapolis, Maryland; Radio Technical Committee for Aeronautics (RTCA, Inc.), Washington, D.C.; and the European Commission for Aviation Electronics (EUROCAE), Paris], Military aircraft have used custom racks, usually because of tight spaces into which equipment must be fit, for example, fighters. The trend is to use commercial racks for cargo, tanker, and bomber aircraft. Mission-essential racks can use single cooling fans if the economic value of lost missions is less than that of a redundant fan. Safety-critical systems require redundant fans or must be uncooled.

B. Standards

The ICAO, a United Nations agency, defines the signals in space for civil navigation and communication aids. Within a vehicle, intersubsystem formats are defined by ARINC for civil aircraft, for example, the ARINC 429 and ARINC 629 buses,[22] and by military standards, for example, MIL-STD-1553 and 1773 data buses. RTCA, Inc., and EUROCAE define the environmental conditions and required testing for avionics on civil aircraft. RTCA and EUROCAE often work together to produce identical standards. Governments define the rules of flight, the electronics that must be in working order before takeoff and during landing, the rules to be followed by the crew in case of failures, traffic separation distances, pilot training, etc. The European Joint Aviation Regulations are being rationalized with U.S. and Japanese regulations. Other countries typically adopt the regulations of the United States Europe, or Japan.

Certification covers all equipment aboard the aircraft at the time of certification, each of which bears a factory part number. Because aircraft remain in service for many decades, far longer than the life span of the electronics, there is a perennial problem in assuring that replacement parts and modifications do not degrade the safety of the aircraft. After many decades, the aircraft manufacturer or subsystem manufacturers may no longer exist. Replacement devices may incorporate different chips, circuit-board materials, assembly processes, connectors, and software. To assist in the certification of replacement parts, the FAA may create a technical standard order (TSO) requiring that quality control systems exist at the manufacturer, that the device meets the FAA's minimum performance standards, that performance data on the product have been submitted to the FAA, and that calibration, test, and installation procedures have been submitted to the FAA. Manufacturers who conform to the TSO mark their equipment and can sell replacement parts. TSOs are typically written for subsystems such as VOR or GPS.

Most parts do not have TSOs. Even new parts made by the original equipment manufacturer may not conform to the original specifications. Replacement parts made by third parties may differ even further from the parts that were on the aircraft when it was certificated. Midlife modifications to the aircraft may add subsystems that were not on the certified aircraft; perhaps parts that were not even known when it was certified. For add-on radios or flight-control equipment, obtaining a TSO or parts manufacturer's authorization (PMA) may require flight testing.

In 2003, standard parts were defined by the FAA as those made to a specification that is complete enough so anyone can build an exact replica and that are so marked. The FAA does not require that replacement standard parts be further certified, although there is considerable question of which parts are standard. Nonstandard parts require a PMA, an FAA certification that the aircraft manufacturer or airline operator agrees that the part does not degrade the safety of the aircraft. Low-budget operators sometimes use replacement parts that do not bear TSO marks, were not produced under PMAs, or are falsely marked. In 1996, the U.S. FAA established a voluntary industry distributor accreditation program that allows replacement parts to be certified. Still, civil aircraft parts practices worldwide are loosely defined and controlled.

The reliability of electronic piece parts can be predicted using historical data collected by the U.S. military in MIL-HDBK-217F (Ref. 23), taking into account the environment in which the parts are used. These parts are assembled into line-replaceable units (LRU). The probability that an LRU performs its function(s) is calculated from the reliability of its parts, allowing for internal redundancy. The probabilities of various kinds of failure are computed from the LRU failure rates, allowing for interconnectivity. If the time to detect and repair a fault (manually or automatically) can be estimated, the availability of a subsystem in executing its various functions can be calculated.

Through the early 1990s, military agencies insisted on custom developments, even when nearly equivalent parts existed. For example, the MIL-STD-1750 computer chip was obsolete by the time it was produced, when Motorola and Intel were making faster and more powerful chips. As budgets became tight in the last decade of the 20th century, the military began to use commercial electronics, often with modifications, for example, for cold-plate cooling and unpressurized bays. Military parts are chosen at the discretion of the aircraft's project officer, who has, in the past, been subject to tight constraints imposed by military specifications.

Commercial parts are certified to perform within specification at temperatures from 0 to 70°C. Industrial parts are certified from −40 to 85°C. Military and space parts are sometimes asked to operate within specification between −55 and 125°C. The differences are in substrate material, encapsulation (plastic vs ceramic), and testing. In 2003, no major manufacturer of chips produces to full military specification. Fortunately, the automobile industry is asking that equipment destined for operation in the engine compartment operate from −40 to 125°C, thus ensuring a future supply of parts for the military and space communities. Meantime, test laboratories are "upscreening" large numbers of commercial parts to select those that perform at extreme temperatures, vibration, and radiation levels.

The selection of quality parts is not enough to ensure a reliable circuit. Voltage and power dissipation must be well below the ratings of parts. Parts must be secured to the circuit board to avoid stressing solder joints during vibration. Flexible leads from chips must allow for differential expansion of board and chip during thermal cycling. Chips must often be hermetically sealed, and boards must be coated to prevent moisture from shorting leads or corroding metals. There is still controversy over whether plastic encapsulation of chips can substitute for the more costly ceramic encapsulation in avionics. In the vicinity of motors, relays, and switching power supplies, magnetic fields must sometimes be excluded from circuitry. Boards must be tested at various stages of assembly and burn in.

In 2003, most avionics boards used through-hole and surface-mount parts, the latter especially in radio-frequency circuits, where small size improves performance. By proper design, testing, and inspection, surface-mount boards are expected to match the reliability and lifespan of lower-density through-hole boards. Chips are cemented directly to boards to relieve loads caused by acceleration and thermal expansion. The use of pin-grid- and ball-grid-array chips in safety-critical systems is still controversial because the interior solder joints cannot be inspected. Surface-mount parts are too small to be hand assembled; hence they incur the high cost of programming pick-and-place robots and bed-of-nails testers, often thousands of dollars per board when they are produced in low production volume. As chip density increases on a board, the cost of repairs increases, thus motivating the use of chips that have been tested before insertion.

C. Computation and Data Transmission

There were no data to be transmitted among subsystems 50 years ago. Each subsystem was self-contained, although it might have had internal analog computing elements (amplifiers, filters, gears, and servomotors). Beginning in the 1960s, digital computers were installed, at first in military aircraft, thus requiring the transmission of data from sensors to computer, computer to computer, computer to actuators, computer to displays, and computer to recorders. These interconnections were individually wired.

Subsystem-dedicated computers have the advantage that software is written by technology specialists and reverification is not complicated by the presence of other subsystem software. Fault tolerance can be hierarchical with most decisions made at the subsystem level and programmed by subsystem experts. By contrast, centralized computers were in favor when minicomputers first flew on aircraft. A single computer, replicated for redundancy, serviced many subsystems. There was a reliability advantage because duplicate power supplies, processors, clocks, interfaces, connectors, and memories were avoided. However, software was written by computer scientists who usually did not understand the underlying technologies. Furthermore, any change in code in one subsystem required reverification of the entire software. In the 1990s, the trend was toward federated systems consisting of an array of subsystem-dedicated computers each having its own level of fault tolerance (high for flight control, low for maintenance recorders). System-level mission, flight management, and maintenance computers may connect to all subsystems but are not safety critical if properly buffered.

Through the 1990s, large aircraft had several thousand pounds of signal wiring and several thousand pounds of power wiring (Fig. 16). Beginning with manned spacecraft and military aircraft in the 1970s, signals were multiplexed on data buses to reduce wiring, and circuit breakers were remotely operated (sometimes via multiplexed buses) to reduce power wiring. ARINC has standardized several data buses for intersubsystem communication on commercial airliners: the ARINC-429 one-way broadcast bus and the ARINC-629 two-way multi-terminal bus (Ref. 5, pp. 693, 694). The U.S. military invented the MIL-1553 (copper wire) and MIL-1773 (fiberoptic) data buses, which they use on many aircraft. Special-purpose control chips are made in quantity for these buses. The RS-422 one-way bus is sometimes used in general aviation (under the name Commercial Standard Bus) as is the aviation standard commercial bus, a two-way bus sanctioned by the General Aviation Manufacturers Association. The automobile industry's two on-board diagnostic buses (Ref. 24) do not transmit safety-critical signals. The industry is considering various safety-signal buses which may also be adopted by the aviation industry since inexpensive parts will become available. Most 1990s buses send data on copper wire. Because some aircraft are built of composite materials, the wiring and avionics are no longer shielded by the metal fuselage but become exposed to man-made electric fields and lightning, thus motivating the use of fiberoptic data transmission. There is constant pressure to increase intersubsystem data rates, especially for nonsafety subsystems such as imaging sensors.

Manned spacecraft led aircraft in the use of multiplexing due to the need to save wire weight. The space shuttle was the first fully multiplexed aircraft in which most sensor and actuator signals are multiplexed and all functions are executed in its nearly centralized computer complex. Hence, multiplex path redundancy is quadruple, matching the needs of the most critical subsystems.

Gemini and Apollo were the first spacecraft to use digital computers (Fig. 17). In the early 1970s, the Space Shuttle Orbiter was designed with four identical, parallel, voting, central digital computers in which navigation, communication, attitude control, failure detection, and other algorithms executed. The four main computers feed redundant display computers and engine-control computers. The intent was to achieve reliability by having as few mini-computers as possible. A fifth main computer was added as a spare, to be powered up during boost and entry but was removed in the 1990s as unnecessary. During the 1990s, the main computer memories were upgraded from 64 to 128 kB. Software and hardware changes require reverifying the entire system on a test bed (avionics integration laboratory). Laptop computers were introduced to support experiments; recent flights have contained more than 20 laptops. In 2006, the computer complex will be entirely replaced on one orbiter, converting the central minicomputer architecture to distributed microcomputers. The other orbiters will be converted at 1-year intervals. The space station has federated subsystem- and experiment-computers interconnected by paths whose redundancy differs by function. Most changes will require reverification of one subsystem, although all external interfaces may also be reverified.

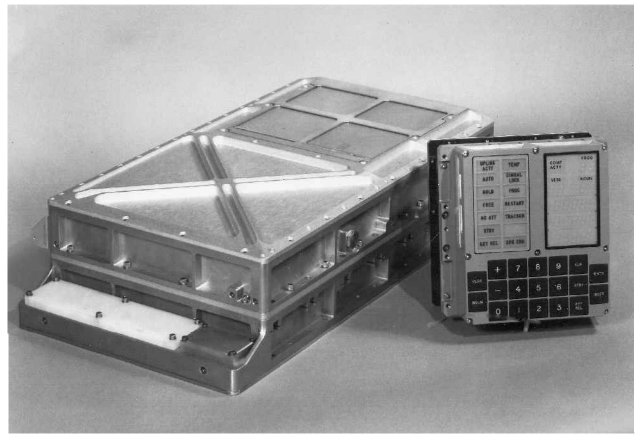

Fig. 17 Apollo guidance computer and display and keyboard assembly, used on the command and lunar modules circa 1969: computer had 2 MHz clock, 23μsec add, 2048 words of core-rope RAM, 36,864 words of core-rope ROM, word length 16 bits, weighed approximately 30 kg, consumed 100 W dc. Display had 2 electroluminescent panels, 10 numerical keys, 2 sign keys, 7 function keys; operator entered 2-digit program or verb (actions) followed by data; weighed approximately 7 kg. Both units hermetically sealed at atmospheric pressure (courtesy of The Charles Stark Draper Laboratory).

D. Software

1. *Software Engineering*

Software was unknown to the Wright brothers and to several generations of pilots and engineers thereafter. It was first introduced in the analog computers of the late 1950s in which flight-control algorithms and stability filters were fixed wired. During design, paper analysis and flight tests confirmed the values of resistors and capacitors in the analog circuits. Digital software was introduced in the North American A3J, Litton Diane (on the Grumman A2F) and other airborne digital computers of the early 1960s. Complex software began with the F-16 mission computer, the space shuttle central computers, and a few aircraft in the 1970s.

Most onboard software executes in hard real time because commands must often be issued within milliseconds of sensor measurements. Early airborne software was assembly coded, that is, written in mnemonics for the executable computer instructions. When high-order equation languages such as FORTRAN became available, they were not used in flight computers because their compilers produced slow, lengthy code (typically 10 times worse than assembly code). In Ref. 25, what may have been the first compiler that translated equations into machine code is described. Since the late 1950s, compilers accept matrix instructions and transcendental functions. Memory was scarce and clocks were slow. (Litton's C-900 had about 8000 bytes of memory, and the Apollo clock ran at about 300 kHz). As semiconductor memory became cheap (compared to dollar-a-bit ferrite cores) and clock speeds passed 1 MHz, onboard algorithms came to be written in new high-order languages, for example, HAL (for the space shuttle), CP-1 (for Navy aircraft), and ADA (for 1980–2000 U.S. defense department code). Their compilers were expensively validated. With cheap memory and fast clocks, the number of compiled instructions was less important.

The earliest avionics software was synchronous; each task executed successively on a fixed-time schedule, ensuring that everything got done in each computing cycle (0.01 s for flight control, 1 s for navigation). Best practice still requires safety-of-flight software to be synchronous. Where there are too many nonsafety tasks to schedule in each cycle, they can compete to execute in noncritical time slots on a prioritized basis, recognizing that not all of them will be done each cycle. In 2003, the trend is toward complex, softer real-time operating systems that allow extensive interrupts but do not guarantee completion. Airborne computers contain several classes of software, of which the following are examples. For the safety of flight class, there are an operating system, certain device drivers and moding, flight control algorithms, power-control algorithms, and display formats. For the mission-essential class, there are device drivers and moding, display formats, navigation, communication, mission replanning, and gunfire and missile control. For the convenience class, there are drivers for flight data recorders and maintenance recorders.

Airborne software is written in modules, by specialists in equipment design or mission design. For reliability, the modules are written as simply as possible following design rules peculiar to each company. The operating system is furnished by the computer manufacturer and must ensure that modules start and finish within a set period, often 1 ms. It often must work with a coprocessor for convolution or fast-Fourier transforms and must have fault-tolerant features such as rollback points and a watchdog timer. Interrupts must be prioritized and consistent with the semaphores that lock the data storage during execution of a module. Operating systems can be written in a high-order language or in assembly code. (In 2003, various dialects of C are in favor.) Except for the hardware drivers and interrupt routines, the classes of software listed above are usually written in a high-order language with plentiful comments for the edification of future modifiers of the code.

Device drivers (keypads, gyroscopes, and actuators) continue to be written in assembly code. The device drivers and high-order code are linked (perhaps compiled into "object code") and tested using approved vehicle dynamic algorithms and sensor models. Testing can be on a general-purpose computer or on an emulation of the flight computer. Modules are tested to verify that they execute correctly, on time, and give correct numerical results.

Once tested, the modules are assembled using software tools and tested in ever larger blocks. Statistics are kept on the rate and type of failures discovered.[26] When the failure rate is sufficiently low, the software is moved to an avionics integration laboratory where it is tested further with simulated and live avionics boxes. As development proceeds, mathematical models are replaced by live hardware in the simulation laboratory. Inputs to the hardware are induced by rotating tables, image synthesizers, or mathematical models. Mathematical models of the aircraft dynamics and sensors must be validated. During testing of the assembled program, engineers and pilots run tests designed to provoke errors. After several years of testing, a software version is deemed ready for release to a working aircraft. Thus, where mission-critical and flight-safety software are in separate computers, development of the latter must begin first. Configuration control is essential during the development process to identify the extent of testing of each version of modules and assembled code. The modularization of airborne code and process-control code are in apparent contrast to the interlocked structure of personal-computer code, in which functions are not simply removable for business reasons.

Airborne code is 10–100 times as expensive per written instruction (whether written in assembler or high-order language) as batch code for record keeping. New projects reuse code sequences where possible to reduce retesting of the modules, even though the assembled code always required retesting. The predictability of software's cost and schedule improved steadily during the 1980s and 1990s (Ref. 27). Those versions that are released are loaded into the flight computers.

The loading of navigation waypoints was discussed in Sec. II.A. Program code is rarely reloaded, but when it is, loading from ground-based computers can take hours. Airplane information management systems (AIMS) and special-purpose loaders reduce loading time. Airlines will sometimes exchange a computer with a preloaded one rather than wait for a real-time download.

2. *Flight-Control Software*

In 1911, aerodynamicist George H. Bryan wrote the linearized equations of angular motion of an airplane, relating torques to angles of attack, side slip, and body rates (see Ref. 1). The constant coefficients (stability derivatives) could be recalculated as aircraft speed and altitude changed, thus giving a sequence of quasi-steady-state solutions because the oscillations were much faster than the rate of change of speed and altitude. The Wright brothers did not know theoretical aerodynamics, but, instead, based their designs on empirical wind-tunnel and flight tests. The Bryan equations have been used ever since to design aircraft of ever increasing performance.

When autopilots came into use in the 1940s, they applied torques to the airplane's control surfaces in response to sensed angular body rates and lateral accelerations. The Bryan equations were used, in simplified analog form, in the autopilots themselves and during the development of the autopilots. Final values of gains and time constants were always set during flight tests and were difficult to change because they were wired as resistors and capacitors. A good autopilot gave rapid response and damped recovery from gusts and pilot inputs, as in the B-47 bomber. Analog autopilots had progressed to the stage where they could adjust their own gains based on measured dynamic pressure. In 2003, linearized equations are still used but are computed digitally as environmental conditions change. Compressibility of the flow and wide ranges of altitude must be included. The computation of the flowfield in real-time in-flight is impossible in 2003. The typical flight-control computer has less than 25% of its software devoted to aerodynamics. The rest is to fault tolerance, moding, calibration, sensor drivers, and actuator drivers as in the cases at the start of this section. Multiaxis Kalman filters are a predictable, if sometimes non-intuitive, solution to three-dimensional control problems.

Wind-tunnel tests validate the stability derivatives. Since the 1960s, variable-stability aircraft became an important tool that would have astonished the Wright brothers (Ref. 1, Chap. 3). Such aircraft have two cockpits, one for a safety pilot who takes off, lands, and is prepared to intervene during tests. The second cockpit is a simulation of the cockpit of the aircraft in design and is coupled to an autopilot whose characteristics duplicate the intended aircraft. An F-104 (without a safety cockpit) and a Gulfstream were rigged to simulate the poweroff landings of Space Shuttle Orbiter during the conceptual phases of design. Variable-stability aircraft are also used for pilot training (Sec. III.F).

Proprietary aerodynamic software is an asset of every airframe company, just as are the jigs that assemble body parts. Data-reduction software is also needed to analyze the results of flight tests on prototypes and for certification. Simplified algorithms are used in flight trainers (Sec. II.F).

Flight-control software is developed and tested analytically, then tested on an iron bird simulator (Sec. II.D).

3. *Air-Data Computation*

The Wright brothers carried no instruments on their first flights. Later aircraft had a barometric altimeter and airspeed indicator (a fluttering tape or anemometer, at first) (Sec. II.B.2). A barometer computes pressure by offsetting for the radioed value of sea-level pressure. The pressure–altitude curve is assumed to be invariant. A pitot tube measures dynamic pressure, which is related to airspeed assuming a fixed air density. As speeds became supersonic, freestream pressure and airspeed had to be calculated from local measurements at the fuselage. Corrections were made with cam mechanisms. In the 1960s, digital computers were able to solve the airflow equations around a body using closed-form equations that calculate freestream speed, pressure, and temperature from body-fixed measurements (Ref. 5, Chap. 8). With the introduction of smooth-skin stealth aircraft in the 1990s, pitot tubes were eliminated, and the flow equations became more complex, based on measurements of pressure at multiple flush body ports. With hypersonic flight of the space shuttle, Mach number increased and the air-data software calculates freestream parameters from measurements at multiple ports below approximately Mach 4. Air-data ports must be kept scrupulously clean.

Air-data computers are usually not internally redundant. Multiple computers are carried or the equations are embedded in several multipurpose computers, for example, flight-control computers. Air-data equations must execute for safety-of-flight.

4. Multisensor Algorithms

In the early days of long-distance flight (before 1960s), a full-time human navigator plotted position on a map based on heading and airspeed (Sec. II.B.1). For intervals of an hour, the calculations were based on a flat Earth, with east–west distances being multiplied by cosine(latitude) to get longitude differences on long legs. Where the navigator could, visual, celestial, or radar fixes were taken to reset position on the map. This procedure was automated in analog computers, then digital computers in the 1960s and 1970s using straightforward geometric algorithms. The computer calculated the intersection of VOR radials or of DME range circles to fix the aircraft's position (Ref. 5, Chap. 2). The algorithms corrected ranges for the aircraft's altitude above the radio station, especially when close to the station. These algorithms became the core of the flight-management computer when off-airways area navigation was permitted.

As multiple navigation aids became available onboard, the most obvious way to mix their outputs was to do a least-squares fit of the data streams. This required storing past data from each navigational aid (navaid) or using a least-squares recursive filter (Ref. 5, Chap. 2). In the late 1950s, several analysts in the United States experimented with algorithms that extended the least-squares method to include dynamic models of their sensors as a way to weight incoming multisensor data so as to form best estimates of the system state. Battin[24] at MIT did so for space trajectories, whereas Swerling at Rand Corporation did so for radars. In 1960, Kalman at Stanford University generalized the method for any number of sensors and presented a systematic matrix-computation procedure for mixing any number of sensors whose properties were describable by linear differential equations. In the 1970s, the Kalman filter came into use as a way to weight the measurements from multiple sensors (at first an inertial system and a radio aid) using a simplified linear dynamic model of each sensor (see Ref. 5). The filter computed a time-varying gain for each sensor. It permitted the estimate of calibration errors in the sensors from a long stream of data. Navigation companies developed proprietary algorithms that reinitialized the covariance matrix to prevent the gains from falling too low, adding pragmatic reasonability tests, suspension of filtering during periods of high-rate maneuvering or sensor gaps, for example, when roll angle shaded an antenna, and changing the linear models slowly as the geometry of the fix changed. Some algorithms process system state vectors, others process raw sensor data. In 1979, the square root formulation triangularized the covariance matrix, thus reducing the amount of computation. Today, with computers of enormous memory and speed, the Kalman filter universally estimates the navigation state, the attitude state, sensor biases, and sometimes clock drift onboard aircraft.

5. Fault-Tolerant Software

Subsystem-level software detects, annunciates, and perhaps corrects failures in sensors, computers, and other electronic boxes. System-level software compares subsystem outputs to detect, annunciate, and perhaps correct subsystem errors (Sec. III.E).

Design features are often included within the software, such as redundant calculations using different algorithms even within the same computer. Deci-second rollback points, for which the entire state is stored, allow recovery from software failures by restarting at the rollback.[28]

Each avionics company has proprietary fault-tolerance algorithms for its own types of equipment. They may compare redundant measurements of position and velocity or may compare GPS pseudoranges or inertial angular pulses. Tests for reasonable changes in a computing interval and for algebraic sign are typical. Voting of multiple measurements is common. Older algorithms averaged but newer ones select the middle, upper-middle, or lower-middle value to prevent huge errors from biasing the average. An early example of voting was in the DC-10 landing system of the early 1970s. It had two dual-channels pairs (four identical analog control channels). A discompare in either pair dropped it out, leaving the other pair online. If both pairs dropped out, a manual landing was required.

E. Subsystem Management

Before 1950, there were few subsystems on an aircraft, for example, fuel, hydraulics, and landing gear. Each subsystem had its own on–off switch, mode switches, indicator lights, and dedicated displays. The crew made all of the system-level decisions. Today, aircraft contain many complex subsystems such as 1) engines, 2) fuel storage and distribution, 3) APU, 4) hydraulic pumps and fluid distribution, 5) air conditioning of crew, passengers, and equipment, 6) deicing, 7) landing gear, 8) fire protection, 9) oxygen distribution and, sometimes, generation, 10) electric power generation and distribution, 11) lighting, interior and exterior, 12) avionics, 13) galley, and 14) military-specialized weapon controls, terrain avoidance, etc. (Sec. III.J).

Each subsystem has modes, data to be input, failure conditions, and reconfiguration commands following failures. These are set by the crew or by a system-level computer.

Until the 1990s, hard-copy user manuals were carried onto the aircraft. The flight engineer used them to diagnose failures and reconfigure the subsystems. In 2003, considerable subsystem management is done by computers that detect failures and show subsystem information including block diagrams with color-coded valves and switches. Boeing calls its monitor AIMS (see the end of Sec. III.D.1 and Ref. 29), whereas Airbus calls theirs electronic centralized aircraft monitor. Nevertheless, hard-copy user manuals are still carried aboard aircraft.

If minutes can be allowed for a decision, the computer can present the choices to the crew for action. If the response must be within seconds (as in flight control during landing or in selecting between upper and lower antennas during roll), the computers must respond automatically and may alert the crew as to what was done. Circuit breakers are often operated manually because of the risk that removing power will prevent automated restoration.

A failure can occur in hardware or in software, either of which can cause out-of-tolerance behavior of the avionics system. The fault is the measurable cause of a failure. It might be low voltage in a power supply, a hard-on failure of an output transistor, or an incorrect block of computer code that was never tested under certain conditions of flight, for example, excess attitude, high sink rate, or late engagement of a sensor. Each device (LRU, which is removable from the aircraft) has built-in test (BIT) circuits that monitor, for example, voltages, memories, registers, amplitudes of analog signals, and clock speed. Manufacturers typically claim that their BIT detects 85–95% of failures.

Avionic systems that can cause loss of life or noncompletion of an important mission detect and perhaps correct for these failures. Avionic systems whose failures cause expensive damage or loss of a reflyable mission can afford to incorporate just enough software and circuitry for fault tolerance to pay for the lifetime risk of loss. In these cases, the circuitry and software must detect and annunciate the failure. Time-critical faults must be reconfigured so the system can continue to operate. Frequently, fault tolerance includes an independent monitor for integrity checks. Yount[30] discusses the architectures of flight-critical systems.

Historically, avionics have not been responsible for loss of life or expensive damage. Flight control, navigation, radios, and gunfire-control could be done manually, albeit with less accuracy and with more difficulty. However, as electronics costs fall, they are being used in safety-of-flight applications. For example, a Category I or II landing aid must detect a failure, allowing the crew to go around without hitting terrain or buildings. However, a Category III landing aid must allow the landing to continue, even if the failure occurs after the engines are throttled back, when go-around is impossible. Hence, Category III failures are time critical.

At the system level, a mission computer or avionics computer monitors the outputs of multiple sensors to determine whether they are consistent and, if not, to identify the failed LRU with the aid of the BIT signals. Bit-by-bit comparison of redundant channels is not practical because addresses, timing, and exact sensor values always differ. Hence, to observe communication errors on the data buses, it is better to compare error codes attached to each message. Avionic computers that receive data from multiple sensors compare the sensors' outputs and infer the existence of sensor faults. Computers that receive data from multiple subsystems compare their outputs and their BIT and infer the existence of subsystem faults. Both kinds of fault data are stored in a maintenance recorder that is accessible to mechanics.

With enough redundancy, the algorithms can reconfigure, by identifying the bad signals, ignoring them, and continuing to operate. Reconfigured systems must alert the operators and maintenance personnel that a masked failure exists and must be repaired even though the system seems to work normally. Osder[31] reviews the status of redundancy management in 1999. The architectures of redundant systems are discussed by Hammett.[32] System-wide diagnosis succeeds best when capable system engineers enforce a common policy of BIT and fault tolerance on an aircraft or spacecraft. Regulatory rules typically prohibit safety-of-flight systems from taking off with a masked failure.

Inertial sensors can be replicated; jumbo jets carry three complete inertial measurement units (IMUs). Alternatively, the IMU can have multiple internal gyros and accelerometers. For example, an IMU can have three two-axis gyroscopes or four one-axis accelerometers. Redundant axes allow the detection of one or more failures and, with still more redundancy, the correction of one or two failures. In the 1970s, experimental IMUs were built with six one-axis sensors spread evenly over the sphere, allowing the detection and correction of any two failures. Manned vehicles usually use replicated IMUs.

An on-demand test is needed that activates all of the displays (gauges and screens) with a test pattern that is easily perceived as normal by the crew. Fault tolerance is linked to postmission repair techniques and mean time to repair. Status lights on the circuit boards and removable units commonly show the BIT results of the unit. The avionics designer must be aware of how LRUs will be tested and repaired at each airbase. Usually, a simple test is run on the LRU, and it is sent to the manufacturer if the test fails. Many airline and military personnel say that 50% of removed LRUs test "good" at the manufacturer, but the technicians often prefer to change an LRU than to diagnose it, under the pressure of flight schedules.

Before the 1990s, large aircraft carried analog data recorders that scratched four tracks of data (altitude, airspeed, heading, and vertical acceleration) onto a metal foil that was periodically replaced. The recorder was installed at the rear of the aircraft and was designed to survive a crash, whereupon the foil was readout. The first digital recorders sampled 17 points (tracks) and worked with external analog-to-digital converters. In 2003, new large aircraft carry ejectable, survivable data/voice recorders with internal emergency locator transmitters (Sec. IV). These digital recorders store 88 to 300 points, sampled as often as four times per second for 25 h. Survivable voice recorders store four analog audio channels for 30 min. Both overwrite stale data and audio unless they are read-out or removed.

Some airlines and military organizations are experimenting with the transmission of selected faults by radio to the next airport to speed up the process of turning the aircraft around.[33] Engine vibration and temperatures have been recorded in an attempt to extend the time between overhauls.

F. Landing Aids

Before 1950, all aircraft landed visually. A blind landing using primitive instruments had been demonstrated in 1929 but was in no way operational. During World War II, the ground-controlled approach (GCA) was perfected, mostly for military use. A height-finding radar at the airport monitored the landing while a human in the radar room spoke to the pilot, guiding up–down and left–right. The pilot was supposed to see the runway before landing but stories were told of GCA touchdowns in fog, as during the Berlin airlift in 1948–1949. Fortunately, those aircraft were small, slow, piston powered, and, therefore, tolerant of piloting errors.

In the 1950s, the ILS (Ref. 5, Chap. 13.5) replaced GCA for civil operations. Ground-based ILS transmitters create a straight-line path along the runway centerline, about 3-deg above the horizontal, from about 15 miles from touchdown to the runway threshold. ILS has been in use since World War II. In 2003, there are about a thousand installations in the United States alone.

According to ICAO rules worldwide, an approach may not be attempted unless the visibility [runway visual range (RVR)] exceeds a threshold. A decision height (DH) is defined for each runway at which an abort is required if the runway lights are not visible. At Category I airports, the RVR is 800 m and the DH is 60 m. The desired positioning accuracy on the approach is about 16 m horizontally and 8 m vertically, 2 sigma (encompassing 95% of all Category I landings). At Category II airports, the RVR is 350 m and the DH is 30 m. At Category III airports, the RVR varies from 50 to 200 m and the DH from 0 to 30 m. At Category III, the avionics must be fault tolerant, and crews must be specially trained. If the throttles are pushed forward for an abort below 20 m altitude, many jet aircraft will touch the runway. Hence, fail-operational autopilots and fail-operational receivers are required for DH less than 20 m.

ILS continues to be used for Category I and II landings and for most Category III. Aircraft approaching on the ILS beam may measure range with a DME and may measure altitude above local terrain with a radar altimeter. ILS is likely to be replaced by a DGPS local area augmentation system (LAAS) or microwave landing system (MLS) for Categories IIIB and IIIC. The goal is to land without DH and RVR restrictions, a condition called Category IIIC, not yet authorized anywhere in the world. The first Category IIIA authorization was for a Lockheed 1011 in 1971.

An MLS (Ref. 5, pp. 620–628) was standardized by ICAO. A large fraction of the major runways in northwestern Europe have been equipped with it, as are a few at international gateways in the northeastern and northwestern United States. For about 15 years, the U.S. military and NATO have been using portable MLS for fighters and cargo aircraft that must land on unimproved runways hastily scraped near battlefields. MLS allows curved approaches at a crew-selected glide-slope angle. MLS is relatively impervious to reflections from buildings and taxiing aircraft and, hence, permits more aircraft operations per hour. It can be erected and calibrated in a few hours, vs weeks for an ILS.

The differential GPS LAAS is being tested for precision approaches in the United States, in which height above the runway and horizontal position are measured to an accuracy of about 1 m by GPS with inertial smoothing.[34] Differential stations and pseudolites (emitting GPS-like signals) at the airport permit three-dimensional positioning and failure detection. Because aircraft carry GPS and inertial systems for en route use, little additional airborne equipment is needed for LAAS. A few LAAS stations at an airport can cover both ends of all runways. The probable future of LAAS is discussed in Sec. IV.

If LAAS succeeds, MLS deployment may be arrested until GPS is decommissioned. In the 1990s, researchers were testing synthetic-vision landing aids, usually using millimeter-wave radars, that display images of the runway on a HUD. The amount of image processing is reduced if corner reflectors or transponders are positioned along the edges of the runway. Synthetic vision will probably first be used by the military on unprepared airstrips.

The nationwide WAAS (Sec. II.B.3) is intended for en route navigation and nonprecision approaches. It may be certifiable for Category I approaches, depending on the result of extensive tests being conducted mostly in the United States. A European version of WAAS may rely on Galileo (GLONASS, Eurosatellites, and GPS). Loran is a possible monitor for nonprecision and Category I approaches. Multimode GPS–loran sets were being analyzed and tested in the late 1990s, sometimes with ILS and MLS. Software would compare the sensors, make a best estimate of the aircraft's state vector, display flight-path deviation, and annunciate discrepancies.

Landing on aircraft carriers is discussed at length in Ref. 5, Chap. 13.8. Space Shuttle Orbiter landings are simulated on NASA's four Gulfstream aircraft, whose left cockpits emulate the orbiter and whose right cockpits have conventional Gulfstream instruments. The Gulfstream emulates the steep 20-deg flight path of the orbiter by using reverse thrust in flight. In orbiter emulation mode, the Gulfstream's flight controls emulate the much heavier, less stable

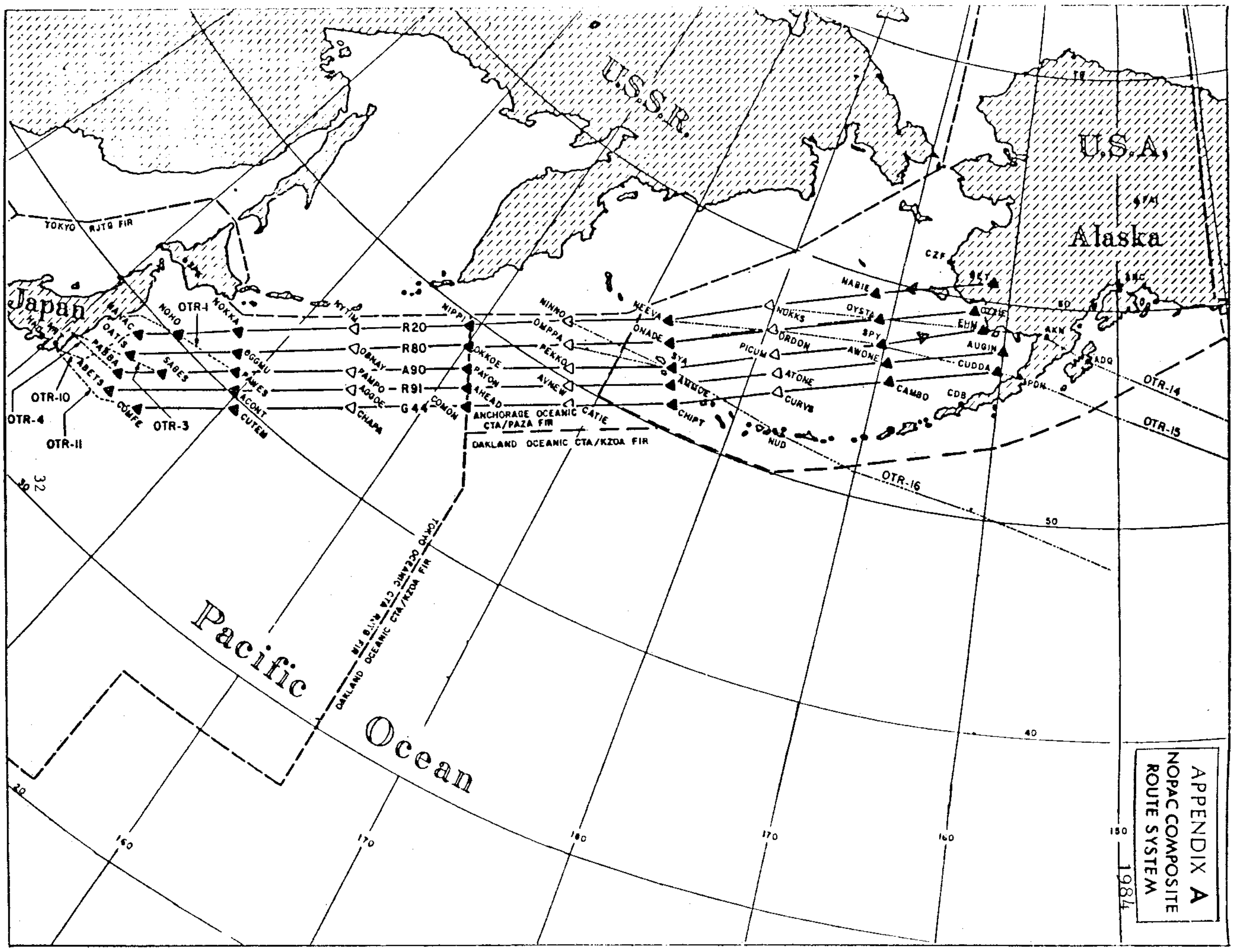

Fig. 18 Pacific ocean tracks, circa 1984 (FAA chart).

orbiter. Crews are trained intensively in the Gulfstreams for the final approach below about 6000 m.

G. Air-Traffic Control

In the 1920s, the earliest airways were lighted by flashing lamps on towers. The airways connected cities whose roofs were painted with the city's name. In the 1930s, four-course radio ranges (Ref. 4, Chap. 2) were installed in the United States that guided aircraft along the lighted airways in foul weather. At the start of World War II, there were 12 traffic-control centers and 40,000 km of lighted airways in the United States. Routes were divided into 1000-ft-high altitude layers and into horizontal blocks between radio beacons. Aircraft reported entering a block whereupon the controllers closed the block until the aircraft reported leaving. This was a direct outgrowth of railroad practice (Ref. 2, p. 231). The advent of jet aircraft extended the airways above 29,000 ft with 2000-ft vertical spacing [being reduced to 1000 ft world-wide (Sec. II.B.2)].

After World War II, ICAO chose the U.S. VOR at 108-118 MHz to mark overland airways. VORs were installed throughout the west and at international entry points in the former Soviet Union and China. They are still the mainstay of overland civil navigation, worldwide.

Based on VOR, an elaborate system of air-traffic control has evolved overland in the industrialized world. The airspace is divided into sectors in which human controllers are responsible for issuing instructions. En route airspace, terminal airspace, and airport control zones each have their own radio frequencies and navigation aids (Ref. 5, Chap. 14). Most oceans are free-flight areas, usually with flight information advisories of known traffic supplied by oceanic control centers. The north Atlantic and north Pacific have tracks, 50–100 n miles apart, in which clearances are issued (Fig. 18). Navigation on these airways is described in Sec. II.B.3.

Congestion on airways was relieved beginning in the 1970s by area navigation (R-Nav), in which new airways were created between phantom VORs (to save the cost of adding new VOR stations). Area-navigation computers use signals from existing VORs and DMEs to calculate the departure from these airways and the distance along them (Ref. 5, pp. 42–44). As inertial navigators and GPS became prevalent, free flight was introduced in the en route space outside terminal areas.[35] Suitably equipped aircraft can fly off airways and are assured separation. Conflict-prediction software in the traffic-control centers assists controllers, whereas TCAS or ADS-B (Sec. II.E) on the aircraft assists pilots. A modern control center has excess work stations that can be used for training, either by shadowing actual flights or by generating synthetic air traffic.

The airspace over northwestern Europe is forecast to saturate in the first decade of 2000, resulting in delays and quotas unless improved avionics can process more aircraft. Reduced vertical separation (Sec. II.B.2) has been one response. A continentwide air-traffic-control system will be another. The United Kingdom has consolidated all its en route domestic and oceanic traffic control in two centers. A central European center is being built in Vienna, which will consolidate the en route airspace of eight or more countries without regard to national boundaries. Five flow-control centers issue clearances to aircraft that cross national boundaries. Yet, many European nations refuse to cede sovereignty of their airspace to an international body such as Eurocontrol. NATO insists on its own control of European military traffic. With frequent handoffs and the complexities of assigning aircraft to nonconflicting altitudes,

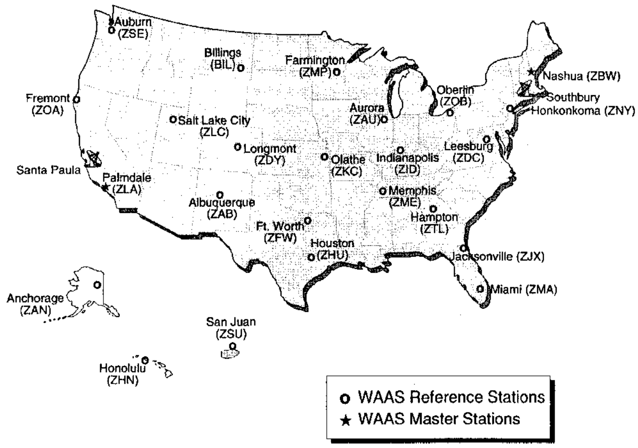

Fig. 19 Candidate DGPS sites in United States for aeronautical WAAS (from Ref. 36).

accidents and delays are inevitable (Sec. II.E). Africa has widespread, uncoordinated control of overland and oceanic traffic.

GPS is accurate enough (better than 20 m with an aviation-qualified receiver) to keep en route aircraft within airways, but failures cannot always be detected. Hours may elapse after a satellite failure before its status bit is reset from the ground. Hence as GPS replaces the network of VORs, WAAS (DGPS, Sec. II.B) will provide navigation and failure detection en route.[36] Experiments indicate that fewer than 50 ground stations will cover the entire continental United States, transmitting corrections via vhf radio, satellite or mode-S links (Fig. 19). WAAS will navigate non-precision landings, whereas vertical navigation will be barometric. Japan is planning a WAAS-like network using a geosynchronous communication–navigation satellite. It will reduce separation over land and on Pacific routes under Japanese control.

Enroute vertical navigation became especially important when fuel prices increased in the mid-1970s. Four-dimensional navigation computers (sometimes called flight management systems) compute optimized climb and descent profiles and control the throttles to place the aircraft at a horizontal and vertical point in space at a desired time. This allows higher density of traffic if controllers can route aircraft in "tubes" rather than clear all of the airspace above a climbing aircraft or below a descending aircraft. Tubes are of most immediate interest in the congested airspace of northwest Europe. In 2000, the U.S. FAA established low-altitude arrival/departure routes that are tubes underlying en route space.

When the Wright brothers flew, no human had reached the north or south pole. In 2003, flights of 6500 n miles over the arctic have begun, connecting the eastern United States to Hong Kong, India, and Singapore, and connecting western Europe to eastern Asia. Redundant onboard navigation and satellite radios are required. For twin-engine aircraft, an emergency field with fuel, medical services, and rescue staff is required within 200-min flying time of all points on the route. Hence, Siberian airways, airports, and surveillance radars are emerging in the 2000s to serve these flights, at a substantial overflight fee.

H. Weather

The Wright brothers flew in steady ocean winds during clear weather. They had no need for forecasts of winds aloft, icing, or volcanic ash. Before weather satellites, pilots' information about weather was limited to preflight briefings, voice reports from ground stations, and visual observations in flight. The preflight briefing was based on reports from a few airports and from imprecise presatellite weather bureau forecasts. Storms came onto land from the oceans without warning. When flying in instrument weather, aircraft commonly blundered into embedded thunderstorms. Aircraft were often lost due to weather, especially on flights in undeveloped areas.

In-flight wind was not measurable directly. Overland, pilots could observe the passing terrain through an optical drift meter, thus visually reading the drift (or "crab") angle. From airspeed and drift angle, they could manually calculate the crosswind component. By comparing the time between fixes with the measured airspeed (if flying a straight line at constant airspeed), they could estimate the along-track component of wind velocity. In 2003, wind velocity is continuously measured in aircraft that carry both inertial navigators and air-data systems. The inertial system measures ground velocity while the air-data system measures airspeed along axis. The vector difference is the horizontal wind vector.

Modern pilots, civil or military, must know the present terminal area weather (for example, barometric pressure, wind velocity, and temperature for takeoff), forecast en route weather (for example, winds aloft for route planning and fuel consumption), and forecast terminal weather at their intended and alternate destinations. They get this preflight information from their airline or military meteorologist or from internet sites. Airline and military pilots do not usually select their own routes and altitudes; dispatchers do it for them. Once airborne, the pilots may choose alternate routes or may be told to use an alternate route by air-traffic control. They would like access to weather information in-flight.

The first in-flight avionic aid to avoiding weather was the airborne nose-mounted weather radar, which gave the pilot an image of water vapor ahead of the aircraft at X-band, thus delineating storms. They were first installed on commercial aircraft in 1955. In uncontrolled airspace, the pilot could maneuver around the storm freely; in controlled airspace, clearance to maneuver was requested. Modern airborne weather-radars show the Doppler-derived speeds of water droplets in false color, thus displaying the intensity of storms. In newer aircraft, the weather display is often superimposed on the HSD, thus allowing the crew to be aware of all information in the horizontal plane. Experiments in the 2000s uplinked ground weather maps for onboard display of windshear, icing, and thunderstorms on the HSD. A declutter switch is helpful.

In aircraft without weather radar, thunderstorms can be detected onboard by two nose-mounted antennas 4 in. apart that measure the time delay in receiving lightning pulses. The relative bearing of the lightning strike thus obtained is inaccurate but good enough to maneuver away from the storm.

Wind-shear describes two phenomena:

1) One form of wind-shear consists of microburst cells that are active within 1000 ft above the ground, caused by downflowing air spreading over the ground. Microbursts might be detected while landing by observing the Doppler shift of returns from water particles on the weather radar.

2) The other form of wind-shear is clear-air turbulence at cruising altitude, caused by speed gradients in the horizontally moving air mass. Clear air has few water droplets; hence, speed gradients are not easily detected. In developed areas, pilot reports are collected by traffic controllers, who develop a mental image of wind shears at cruising altitudes and broadcast the information to pilots by voice. Radiosonde balloons, tracked by radar, collect sporadic high-altitude wind velocities.

The backscatter from laser beams shows a Doppler shift when reflecting from water droplets and dust. Temperature profiles have been interpreted in terms of wind shear. Vertical acceleration profiles and rotational motions of the aircraft have been interpreted in terms of wind shear. Simulations show that 20 s of warning is desirable in cruise and landing to allow the crew to adjust power to the impending encounter with wind shear.

On the ground, weather and air traffic are observed with different radars. In 2003, NEXRAD weather radars are being installed throughout the United States. They transmit images en route storm activity to traffic-control centers, where humans voice link the information to nearby aircraft. Experiments have been made to uplink these radar images directly to aircraft.

At U.S. airports, 47 terminal Doppler weather radars [(TDWR) at C band] are being installed in 2003 to observe the glide path and transmit microburst information to tower operators who voice link it to crews. TDWR can also detect wing-tip vortices of heavy aircraft that can upset lighter aircraft following too closely.

Ice adds weight to an aircraft and distorts the airflow around the wing, control surfaces, propeller, and helicopter rotor. Chunks of ice can damage turbine engines. Protection against icing is, even now, entirely manual; the crew turns on pitot heaters, carburetor heater, and deicing boots on the leading edge of wings and propellers when they suspect icing, often by observing glaze on the wings. Heat comes from the engine's exhaust, turbo/compressors, or electric resistors.

Capacitive, optical and piezoelectric ice detectors are available in 2003, some of which glue to the aircraft's skin. They can alarm the crew, turn on deicing boots, or turn on hot airflow to leading edges. (In many aircraft, the pilots cannot see the wings.) The rate of accretion can be measured. A typical sensor is a piezoelectric crystal whose vibration frequency increases when loaded by a sheet of ice more than 0.5-mm thick. Ice detection in the air ahead might be done by processing the weather radar image and displaying ice on the HSD along with microbursts, storms, and nearby traffic. However, ice can form on the wings when an aircraft with cold fuel tanks descends through moist air, in which case looking ahead is useless.

I. Rescue

In 2003, engines fail far less often than they did before World War II. Nevertheless, aircraft are lost at sea due to engine failure or fire, during landings, and controlled flight into terrain. Military aircraft are downed due to enemy action.

Before the 1970s, the only electronic aids to rescuing downed airmen (or sailors) were radio transmissions. National coast guards patrolled waters close to shore and, in the United States, the Civil Air Patrol searched overland for aircraft that were overdue in closing their flight plans. Coast Guard shore stations were able to triangulate the position of a prolonged transmission, as the U.S. and British navies learned to do during World War II. However, because many aircraft were lost far at sea, in mountains, or in countries without patrols, surviving airmen and sailors were usually on their own. Military search and rescue rarely used navigation aids.

In developed countries, all aircraft are required to carry an aft-mounted emergency locator transmitter (ELT), and all ships are required to carry an ELT on a float that detaches from the top of a mast. ELTs emit a characteristic warbling tone on one or more emergency frequencies (121.5, 243, and 406 MHz).

During the 1980s, the United States and Russia equipped several satellites with transponders that rebroadcast ELT emissions. Ground stations in cooperating countries measure the Doppler shift history of the rebroadcast ELT transmissions and compute the approximate position of the emergency transmitter. At 406 MHz, accuracy is 5–15 km; at the other frequencies, accuracy is 15–30 km. Thousands of rescues have been made using the system, named COSPAS in the former Soviet Union and SARSAT in the west. For example, in India hundreds of fishermen have been rescued as a result of these transmissions.

Modern military search-and-rescue missions resemble penetration missions. Navigation allows the aircraft to fly minimum-risk paths inbound and outbound, based on the location of enemy radars and missile sites. The onboard detection of enemy radars may, in real time, modify the path that was chosen preflight. In 2003, hand-held beacons allowed survivors to transmit spread-spectrum signals via satellite that identify themselves, their condition, and their GPS position.

J. Military Avionics

The military has special needs that are not met by civil avionics. The following are examples of those needs.

1) Land on carriers in foul weather and at night (Ref. 5, Chap. 13.8).

2) Locate tankers for refueling and stationkeeping (Ref. 5, p. 6).

3) Stationkeep in formation flight. (This was always done manually in the 20th century but is soon to be done with DGPS).

4) Land at unimproved airports equipped with portable navaids (Ref. 5, p. 627).

5) Drop parachute cargo at precise locations.

6) Find and identify targets previously located by intelligence. Drop guided and unguided bombs on them.

7) Find other aircraft using air-to-air radar and attack them with gunfire, missiles, or radiation.[37] Arm and aim air-to-air and air-to-ground missiles.[35] Figure 20 shows a fire-control radar installed in an F-16, with the nose opened.

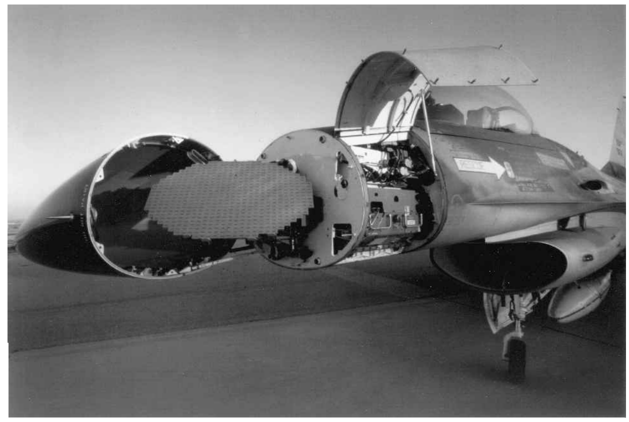

Fig. 20 Nose-mounted multimode radar antenna in an F-16 with radome open: simultaneous tracking of multiple airborne targets, mapping of the ground, and measurement of velocity. APG-68 radar used in many fighter aircraft worldwide (courtesy of Northrop Grumman Corporation).

8) Guide cruise missiles to their targets. At the turn of the 21st century, they are inertially guided with midcourse terrain-match updates (TERCOM, Ref. 5, Chap. 2.6) or terminal-area scene matchers.

9) Plan missions to avoid radars and antiaircraft missiles. Replan in flight as new sites are identified. Fly at tree-top altitude to reduce exposure to radars and missiles (Ref. 5, p. 17).

10) Detect enemy radars, locate them, and identify their type by analyzing their emissions.[38]

11) Suppress enemy radars and communications by active jamming.

12) Divert or destroy guided missiles by interfering with their radar or optical guidance signals.

13) Achieve radar stealth, to allow concealed approaches to targets, for example, by interfering with radar returns.

14) Patrol national borders to detect and interdict illegal immigrants or contraband.

15) Support ground troops on battlefields, for example, by dropping guided or unguided bombs. This requires communication on frequencies and formats employed by the ground forces, for example, 30–88 MHz FM.

16) Operate unmanned vehicles for observation and weapon delivery. Miniaturization and high data rates characterize their avionics (next section).

17) Identify friendly forces so they will not be fired on. There is recurring talk of shooting at vehicles that do not reply to identification friend or foe (IFF) interrogations, but failure of equipment and inability to distribute current encryption keys has precluded such stringent rules of engagement. Stringent rules lead to friendly fire casualties.

18) Control flight at angles of attack greater than 45 deg. Roll the vehicle around the velocity vector rather than the longitudinal axis.

19) Defend aircraft-carrier task forces with far-ranging patrols of surveillance aircraft, helicopters, and submarines.

20) Locate and attack submarines (in 2003, with magnetic anomaly detectors and water-dropped sonobuoys).

21) Command and control battlefields and ships at various levels of the military hierarchy. Many command centers interface to aircraft.

22) Rescue soldiers, airmen, and sailors, often in hostile territory (Sec. III.I).

23) Train crews in all tasks from operating complex equipment, for example, flying aircraft and helicopters, to maintaining equipment, to fighting on battlefields.

The military has developed specialized, low-production volume and, therefore, costly avionic devices to meet these and other needs. For example, the joint tactical information distribution system permits aircraft, ground forces, and naval forces to exchange data, such as each other's positions, target positions, and voice messages in a secure manner. Airborne terminals are said to cost more than $250,000 each, exclusive of development costs. Specialized military avionics are often installed in self-contained pods carried in wing-mounted weapon racks. They are, for example, infrared imagery, collection of signal intelligence, or electronic warfare (jamming). Some stealth aircraft mount infrared equipment in deployable turrets. Avionics on some military aircraft are exposed to unusual stress: 1) high-impact landings on aircraft carriers; 2) exposure to nuclear radiation in wartime; 3) gunfire penetrating the skin, hence, the need for physical separation of redundant control cables, electric wires, and hydraulic lines; 4) shock produced by guns that are sometimes mounted near avionics equipment; 5) high gravitational acceleration maneuvers of fighter aircraft; and 6) exposure to low atmospheric pressure in the open bays of aircraft. Avionic packages subject to such stresses require special design, rugged parts, and additional testing.

K. Unmanned Air Vehicles

These flying robots emerged from towed banners that were used for target practice during and just after World War II. The banners were replaced by towed surplus gliders and then by remote-piloted drones during the 1960s. Those drones took off and flew straight lines and steady turns as practice targets for fighter aircraft shooting guns and missiles and for ground missile batteries.

In the 1970s, chip-scale circuits and servomotors became available that allowed model airplane enthusiasts to pilot their aircraft remotely with three-axis attitude control, throttle control, and a few discretes to deploy dethermalizers or parachutes. Late in that decade, remotely piloted model helicopters became available commercially. They could carry virtually no payload and so no military or commercial applications were found.

During the Viet Nam War, brave F-4 pilots were routinely asked to fly head-on to antiaircraft batteries to launch missiles. They experienced horrendous losses. As a result, unmanned aircraft were developed to release missiles that sought the radars at the antiaircraft sites. The remote pilot was in a trailer on the ground. They were recovered by landing on a runway. The development of launch-and-leave missiles, dropped from a manned aircraft, made these attack robots obsolete. Reconnaissance versions of these unmanned air vehicles or remotely piloted vehicles were developed that carried video cameras and wideband communication links for real-time transmission. Unmanned reconnaissance vehicles were widely used during the Gulf War.

In 2003, the sole applications of unmanned air vehicles seem to be military. There seem to be two trends.

1) Large, complex vehicles carry sensors and weapons. They are the size of fighter aircraft and are propeller or jet powered. They have fault-tolerant subsystems to permit recovery and reuse. They are becoming more autonomous so that a ground operator can fly several of them. With tight command-and-control, the remote pilot can find a target, identify it, and attack it. These decisions are less likely to be autonomous than the routes and pointing angles. Their technology resembles that of deep space robots.

2) The second trend is to small vehicles, from 6 in. to 6 ft in size. They can look around corners, over hills, and onto roof-tops; explore the inside of buildings; or hover over parts of a battlefield. When fully developed, they will use microminiature valves and sensors, have no redundancy, be battery powered, and be recoverable but cheap enough to be disposable. Fixed wing, helicopter, and ornithopter versions are in development, each of which has unique flight-control problems.

Further in the future, swarms of unmanned air vehicles (UAVs) may cooperate by partitioning search areas or attacking targets sequentially in response to group commands. In 2003, UAVs fly in military restricted airspace, but planning is underway to fly large UAVs routinely in civil airspace.

The subsystems of unmanned vehicles are the same as those of manned aircraft except that there is no need for life support and armor. There have been few, if any, commercial applications.

IV. Future Trends

Avionics improvements continue to be limited by low-volume production. Investment in complex software and application-specific integrated circuits is often not economical for low volume. The emergence of a worldwide duopoly in the design and production of large commercial aircraft at the end of the 1990s forced a reduction in the number of avionics manufacturers. A near-duopoly exists for U.S. military aircraft. Hence, in 1999, mergers created two large avionic suppliers in the United States. At worst, these consolidations will stifle new ideas, reduce salaries, and discourage smart engineers from entering the avionics and large-aircraft industries. If so, progress in avionics may be led by commuter and general-aviation aircraft, where competition still reigns (about 10 manufacturers in 2003). Passenger service electronics will be a growth area in large aircraft.

Military-specific chips are desirable, for example, for radar processing and electronic warfare; however military development budgets are declining worldwide despite the terrorist attacks of 2001. Even if the military services of several countries collaborated on the design and testing of a custom chip, production would be low, and development costs would constitute a large fraction of the chip's price (as did the U.S. military's very high-speed integrated circuits of the 1970s). Hence, military services will continue to buy computer, digital-signal processing, and communication chips and adapt them, burn them in, or screen them in severe environments when needed. They will continue to customize gate arrays where budgets permit.

For more than two decades, conformal packaging has been proposed. In one version, chips and passive components would be mounted on flexible circuit boards. In another version, circuit boards (rigid or flexible) would be built into a vehicle's skin panel, with integral connectors for power and signals. At first, the panels would be nonstructural, mounted as are present antennas. Later, the electronics might be mounted on structural elements and installed during fabrication of the vehicle. Cost, cooling, and later upgrades discourage such developments except for military services with large budgets.

Aircraft and spacecraft remain in operation for decades, far longer than the life of consumer electronics products. To service avionics, owners either buy extra spare boards or purchase newly designed boards that are functionally equivalent. Most aircraft and manned spacecraft replace their entire avionics suites every 15–20 years. Most wiring is replaced during these upgrades; perhaps all wiring should be replaced.

Power generation and distribution on aircraft will exceed 250 V, probably at dc due to the high efficiency of switching power converters, to reduce the weight of wire and magnetic equipment. Fiberoptic transmission of data will become more common, at least for mission-critical and safety-critical data as a way to increase immunity to lightning and man-made radiation.

Actuators for flight control will contain more fault-tolerant features. All-electric actuation may begin to replace electrohydraulic actuation in control surfaces other than trim.

Light aircraft will probably adopt the 42-V dc systems shortly to be introduced into automobiles because reliable, inexpensive equipment will be available. All aircraft will adopt circuit breakers that detect arcing as well as overcurrents, to protect against damaged wiring.

Expensive laboratory and flight-test beds will continue to evaluate equipment and flight procedures, develop software, test responses to failure modes, and test interference among radiating equipments. Public demand for reliability of aircraft will strengthen the need for test beds, and the duopoly of large manufacturers will be able to raise the price of their vehicles to cover these costs.

High-fidelity training simulators will continue to replace flying time as fuel costs rise during the 21st century. Part-task computer-based trainers will teach crews how to use the keyboards and displays of flight-management systems, inertial navigation systems, communication panels, etc. It is possible that the existence of a duopoly in large aircraft will force the standardization of graphic user interfaces, to the benefit of crews and flight safety. A worldwide English-language standard is most probable; a U.S. standard, a European standard, and an Asian standard for ideographic languages is the worst case.

ICAO has encouraged its member countries to adopt space-based navigation and communication, a program called Future Air Navigation System (FANS). In 2003, it is already being used in procedural airspace (over oceans and undeveloped land areas) and may eventually replace ground-based navaids everywhere. With worldwide GPS in routine use, civil inertial systems will be less accurate, serving only to measure attitude and angular rate, filter GPS landings, and detect failures. They will probably fit into displays behind the instrument panel (as directional and vertical gyros do). Military users might continue to purchase a few precise inertial systems, for example, to measure the velocity of an aircraft that is delivering weapons. These ultralow-volume precise inertial systems will be costly.

WAAS is the likely en route, nonprecision landing, and Category I landing aid, especially in areas that are not now equipped with ILS. LAAS is the likely Category III landing aid. The roles of radar surveillance, mode-S, ILS, MLS, TCAS, ADS-B, and private communication links are not clear. Flush antennas and air-data ports will reduce drag and radar cross section.

Looking even further ahead, private communication–navigation satellites will be in routine service, for example, Iridium, Thuraya, and INMARSAT, offering pay-per-call communication, with navigation for a small extra charge. Thus, in the second decade of the 2000s, GPS may be decommissioned because user charges are not recoverable by the U.S. taxpayers (who subsidize users worldwide) as they would be for private systems. If so, inertial navigators will return to today's performance levels to extrapolate between intermittent fixes, taken when messages are exchanged with traffic-control authorities. However, communication–navigation satellites may not be suitable as high-category landing aids because signals are discontinuous. Thus, if GPS is decommissioned, LAAS will depend on airport pseudolites or, more likely, airports will prefer MLS. The post-FANS avionic system is not now apparent. The military may learn to treat navigation as a commercially procured service.

Private communication links, for example, in Canada, Mexico, and Australia, are already being used for safety-of-flight traffic-control messages, a technique that is likely to spread. Dedicated aeronautical channels are so busy that costs are unlikely to be reduced by sharing communication channels with terrestrial and marine users. There would be a safety risk that urgent calls, for example, Mayday, would be delayed by frivolous traffic, for example, Internet entertainment. By the end of the first decade of the 21st century, many routine traffic-control messages will be sent via data link on existing vhf radio channels, thus relegating voice to exceptional problems.

Few new airports are being built; only Nagoya in the developed world. Mexico City, Chicago, and Paris are considering but not building new airports. Hence, traffic density can only be increased by clever avionics in the aircraft and in the control centers. The number of ground centers will fall as free flight is implemented and collision avoidance is shared between ground controllers and flight crews. Algorithms in control centers will permit aircraft to be cleared to cross paths in altitude-restricted tubes. The number of oceanic centers and flight information centers will probably be reduced as satellite communications to aircraft become common. A continent-wide European system will be created requiring fewer handoffs.

The relative cost of TCAS (Sec. II.E) vs each aircraft broadcasting its position is still to be determined. Hence, onboard collision avoidance will evolve along two lines.

1) Improved azimuth measurement will permit the calculation of horizontal and vertical maneuvers by TCAS.

2) Each participating aircraft will broadcast ("squitter") its onboard-derived position several times per second so that all aircraft will display nearby aircraft that are properly equipped on their HSDs. The system, called ADS-B, depends on accurate position measurements in a common coordinate frame. Because aircraft cannot make independent decisions on how to maneuver, squittering must include an interaircraft communication link such as the mode-S link used in today's TCAS to coordinate avoidance maneuvers. Squittering will also reduce collisions on runways and taxiways.

As satellite navigation (initially GPS) becomes ubiquitous, ADS-B will be cheaper than TCAS. Both of them require interaircraft communication to coordinate maneuvers so aircraft do not steer into each other while avoiding collision. The vhf communication frequencies (108–137 MHz) and the radar transponder mode-S frequency (1090 MHz) have been proposed. Intentions to maneuver must be known to the ground controllers, who will issue instructions to aircraft not equipped with TCAS or ADS-B.

In the cockpit, clear-air-turbulence detectors are unlikely to have a long-enough range to allow avoidance maneuvers. More likely, the air-traffic-control system will collect turbulence reports, annotate them with position, and uplink a composite image to nearby aircraft for visual display on the HSD. Computer recognition of a limited vocabulary of spoken commands will be included in aircraft and crewed spacecraft to reduce workload. In 2003, there are problems of language, accent, and hoarseness. Thus, for at least a decade, each member of the crew will carry a voice-personalization cassette aboard and use a limited vocabulary.

The HSD and VSD will be overburdened with symbols: steering cues, other traffic, weather, terrain, and turbulence. Colored presentations will differentiate classes of information, and "declutter" switches will help the crew see what is important in each flight phase. HUDs will become more common on aircraft operating in areas of poor landing weather. Micromechanical inertial sensors will be embedded in panel instruments, rather than being installed in the avionic bay.

Fault-tolerant fly-by-wire already permits the design of unstable airframes, stabilized by full-time electronic augmentation. At the turn of the 21st century, tests were being conducted of high-angle-of-attack, steep approaches that require electronic control. There is no indication that unmanned cargo or passenger aircraft would be accepted by passengers, aircraft owners, or residents beneath airways and airports, nor is there evidence that pilotless aircraft would have cost advantages, given the complexity of onboard electronics and the probable need for a remote pilot on the ground. If pilotless gate-to-gate operation becomes possible, the flight crew might consist of one person, backed up by a remote pilot who monitors dozens of aircraft and is prepared to intervene in case of incapacity of the single crew member. A remote pilot would deter hijackers but would encourage attacks on the ground stations, where a hijacker could commandeer scores of aircraft. There is a risk that terrorists will attack parked aircraft, plant explosives, loosen bolts, or jam control surfaces. Thus, aircraft may carry an onboard perimeter-defense package that can be set up when it is parked overnight and that will annunciate the presence of intruders.

The author does not envision the airborne use of the navigation algorithms used by migrating animals because, in a fixed traffic-control environment, their learning features are not important and their errors while adapting to change are dangerous.[39] Migrating birds and fish are adapted to the death of many individuals whereas manned vehicles expect the survival of every individual. Furthermore, the details of those algorithms are not expected to have been deciphered within the next 10 years.

V. Conclusions

Manned aircraft avionics evolved from simple instruments before World War II to complex, automated systems that have reduced civil crew size from four people to two and permitted operations in virtually all weather. The airplane, which began without any electrical equipment except ignition, has become a carrier of passengers, cargo, weapons, and electronic sensors. Civil and military aircraft have features undreamed of in the days of the Wright brothers. After World War II, transistorized electronics permitted widespread innovation in avionics. In the 1970s, avionics became digital with multifunction displays, all of which emulated the earlier analog systems and displays. In the 2000s, wholly new functions are being performed by complex avionics made possible by inexpensive custom chip sets.

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