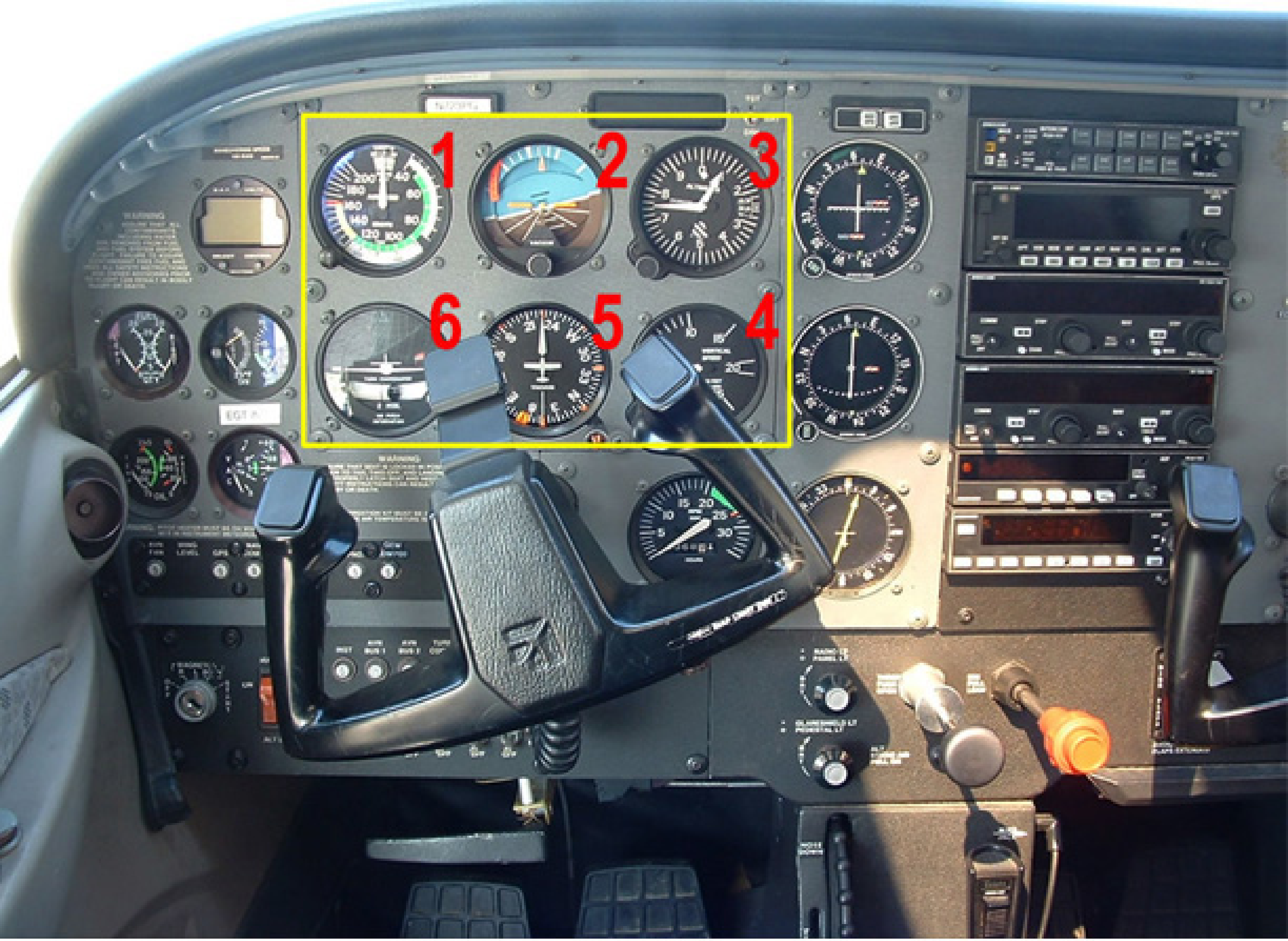

Handbook of Aircraft Instruments

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Chapter 1

Flight Instruments

The cockpit of a Slingsby T-67 Firefly two-seat light airplane. The flight instruments are visible on the left of the instrument panel

Flight instruments are the instruments in the cockpit of an aircraft that provide the pilot with information about the flight situation of that aircraft, such as height, speed and altitude. The flight instruments are of particular use in conditions of poor visibility, such as in clouds, when such information is not available from visual reference outside the aircraft.

The term is sometimes used loosely as a synonym for cockpit instruments as a whole, in which context it can include engine instrument, navigational and communication equipment.

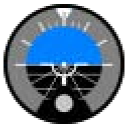
Flight instruments

Most aircraft have these flight instruments:

Altimeter

The altimeter shows the aircraft's altitude above sea-level by measuring the difference between the pressure in a stack of aneroid capsules inside the altimeter and the atmospheric pressure obtained through the static system. It is adjustable for local barometric pressure which must be set correctly to obtain accurate altitude readings. As the aircraft ascends, the capsules expand as the static pressure drops therefore causing the altimeter to indicate a higher altitude. The opposite occurs when descending.

Attitude indicator



The attitude indicator (also known as an *artificial horizon*) shows the aircraft's attitude relative to the horizon. From this the pilot can tell whether the wings are level and if the aircraft nose is pointing above or below the horizon. This is a primary instrument for instrument flight and is also useful in conditions of poor visibility. Pilots are trained to use other instruments in combination should this instrument or its power fail.

Schempp-Hirth Janus-C glider Instrument panel equipped for "cloud flying". The turn and bank indicator is top center. The heading indicator is replaced by a GPS-driven computer with wind and glide data, driving two electronic variometer displays to the right.

Airspeed indicator

The airspeed indicator shows the aircraft's speed (usually in knots) relative to the surrounding air. It works by measuring the ram-air pressure in the aircraft's pitot tube. The indicated airspeed must be corrected for air density (which varies with altitude, temperature and humidity) in order to obtain the true airspeed, and for wind conditions in order to obtain the speed over the ground.

Magnetic compass

The compass shows the aircraft's heading relative to magnetic north. While reliable in steady level flight it can give confusing indications when turning, climbing, descending, or accelerating due to the inclination of the Earth's magnetic field. For this reason, the heading indicator is also used for aircraft operation. For purposes of navigation it may be necessary to correct the direction indicated (which points to a magnetic pole) in order to obtain direction of true north or south (which points to the Earth's axis of rotation).

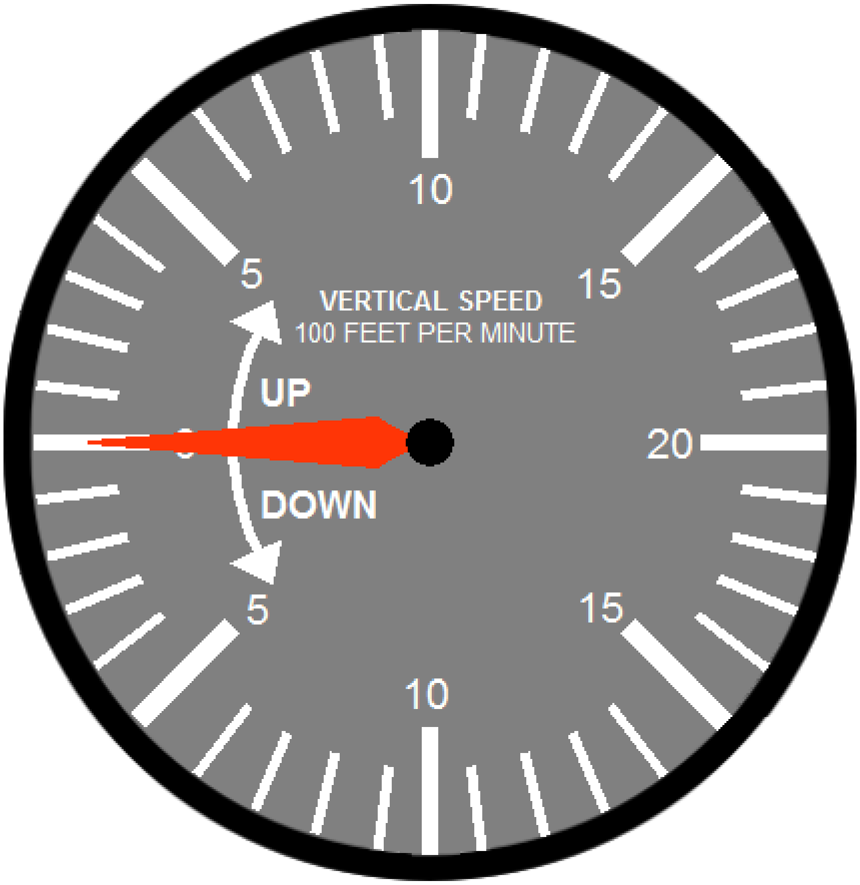
Heading indicator

The heading indicator (also known as the directional gyro, or DG; sometimes also called the gyrocompass, though usually not in aviation applications) displays the aircraft's heading with respect to geographical north. Principle of operation is a spinning gyroscope, and is therefore subject to drift errors (called precession) which must be periodically corrected by calibrating the instrument to the magnetic compass. In many advanced aircraft (including almost all jet aircraft), the heading indicator is replaced by a Horizontal Situation Indicator (HSI) which provides the same heading information, but also assists with navigation

Turn indicator

The turn indicator displays direction of turn and rate of turn. Internally mounted inclinometer displays 'quality' of turn, i.e. whether the turn is correctly coordinated, as opposed to an uncoordinated turn, wherein the aircraft would be in either a slip or a skid. The original turn and bank indicator was replaced in the late 1960s and early '70s by the newer turn coordinator, which is responsive to roll as well as rate of turn, the turn and bank is typically only seen in aircraft manufactured prior to that time, or in gliders manufactured in Europe.

Vertical speed indicator



The VSI (also sometimes called a variometer). Senses changing air pressure, and displays that information to the pilot as a rate of climb or descent in feet per minute, meters per second or knots.

Additional panel instruments that may not be found in smaller aircraft include:

Course deviation indicator

The CDI is an avionics instrument used in aircraft navigation to determine an aircraft's lateral position in relation to a track, which can be provided by a VOR or an Instrument Landing System.

This instrument can also be integrated with the heading indicator in a horizontal situation indicator.

Radio Magnetic Indicator

An RMI is generally coupled to an *automatic direction finder* (ADF), which provides bearing for a tuned Non-directional beacon (NDB). While simple ADF displays may have only one needle, a typical RMI has two, coupled to different ADF receivers, allowing for position fixing using one instrument.

Layout

Six basic instruments in a light twin-engine airplane arranged in a "basic-T". From top left: airspeed indicator, attitude indicator, altimeter, turn coordinator, heading indicator, and vertical speed indicator

Most aircraft are equipped with a standard set of **flight instruments** which give the pilot information about the aircraft's attitude, airspeed, and altitude.

T arrangement

Most aircraft built since about 1953 have four of the **flight instruments** located in a standardized pattern called the T arrangement. The attitude indicator is in the top center, airspeed to the left, altimeter to the right and heading indicator under the attitude indicator. The other two, turn-coordinator and vertical-speed, are usually found under the airspeed and altimeter, but are given more latitude in placement. The magnetic compass will be above the instrument panel, often on the windscreen centerpost. In newer aircraft with glass cockpit instruments the layout of the displays conform to the basic T arrangement.

Basic Six

In 1937 the Royal Air Force (RAF) chose a set of six essential flight instruments which would remain the standard panel used for flying in Instrument Meteorological Conditions (IMC) for the next 20 years. They were:

- airspeed indicator (knots)

- attitude indicator
- vertical speed indicator (rate of climb)
- altimeter
- directional gyro (compass)
- turn and bank indicator (aircraft attitude)

This panel arrangement was incorporated into every RAF aircraft, from the light Tiger Moth, to the heavy Avro Lancaster, and minimized the type-conversion difficulties associated with Blind Flying, since a pilot trained on one aircraft could quickly become accustomed to any other if the instruments were identical.

This Basic Six set, also known as a six pack, was also adopted by commercial aviation. After the Second World War the arrangement was changed to: (top row) airspeed, artificial horizon, altimeter, (bottom row) radio compass, direction indicator, vertical speed.

Chapter 2

Flight Control Modes (Electronic)

Flight control modes (electronic)

New aircraft designs like this Boeing 777 rely on sophisticated flight computers to aid and protect the aircraft in flight. These are governed by computational laws which assign flight control modes during flight

Aircraft with fly-by-wire flight controls require computer *controlled flight control modes* that are capable of determining the operational mode (computational law) of the aircraft.

A reduction of electronic flight control can be caused by the failure of a computational device, such as the flight control computer or an information providing device, such as the ADIRU.

Electronic flight control systems (EFCS) also provide augmentation in normal flight, such as increased protection of the aircraft from overstress or providing a more comfortable flight for passengers by recognizing and correcting for turbulence and providing yaw damping.

Two aircraft manufacturers produce commercial passenger aircraft with primary flight computers that can perform under different flight control modes (or laws). The most well-known are the *Normal, Alternate, Direct* and *Mechanical Laws* of the Airbus A320-A380.

Boeing's fly-by-wire system is used in the Boeing 777. Boeing also has two other commercial aircraft under development, the 787 and the 747-8, which will use fly-by-wire controls.

These newer generation of aircraft use the lighter weight electronic systems to increase safety and performance while lowering aircraft weight. Since these systems can also protect the aircraft from overstress situations, the designers can therefore reduce over-engineered components, further reducing weight.

Philosophies of design

Aircraft designers have created a set of flight control modes that include redundant electronics to safeguard against system failures. Failures can occur singly or combined to render systems inoperable. Pilots must be able to control the aircraft with some, or even none, of the computational electronics functioning. In the case of Airbus the back-ups are the direct and mechanical modes. Boeing's direct mode removes many of the computational 'limitations'.

In older aircraft, control is through the pilot's control column, rudder pedals, trim wheel or throttles that mechanically move cables, pulleys or hydraulic servo valves. These then move control surfaces or change engine settings.

Many newer aircraft replace these mechanical controls with fly-by-wire systems. These aircraft have flight control computers which operate control surfaces, inform the pilot and provide performance information. In older aircraft the pilot's mechanical controls are resisted by the forces acting on the control surface, but nothing prevents the aircraft from stalling, over-speeding or an excessive bank angle at high speed. Fly-by-wire systems limit control surface movements to ensure that aircraft limits are not exceeded.

Another function of flight control laws is to assess the performance of the aircraft under various conditions, such as takeoff, landing or normal cruise when flight control computers partially or completely fail. Designers build in the ability to by-pass the computers or for the standby systems to operate without the computers.

Flight control laws (Airbus)

A330-200 in flight mode

Airbus aircraft designs after the A300/A310 are almost completely controlled by fly-by-wire equipment. These newer aircraft, including the A320, A330, A340, A350 and A380 operate under Airbus flight control Laws. The flight controls on the Airbus 330, for example, are all electronically controlled and hydraulically activated. Some surfaces, such as the rudder, can also be mechanically controlled. While in normal flight the computers act to prevent excessive forces in the pitch and roll.

Airbus 320-100 Cockpit

Illustration of the Air-data reference system on Airbus A330

The aircraft is controlled by three primary control computers (Captain's, First Officer's and Standby) and two secondary control computers (Captain's and First Officer's). In addition there are two Flight Control Data Computers (FCDC) that read information from the sensors, such as air data (airspeed, altitude). This is fed along with GPS data, into three processing units known as ADIRUs (Air data/inertial reference units) which act both as an air data reference and inertial reference. ADIRUs are part of the air data inertial reference system, which, on the Airbus is linked to eight air data modules: three are linked to pitot tubes and five are linked to static sources. Information from the ADIRU is fed into one of several flight control computers (Primary and secondary flight control). The computers also receive information from the control surfaces of the aircraft and from the pilots aircraft control devices and autopilot. Information from these computers is sent both to the pilot's primary flight display and also to the control surfaces.

There are four named flight control laws, however *Alternate Law* consists of two modes, *Alternate Law 1* and *Alternate Law 2*. Each of these modes have different sub modes: ground mode, flight mode and flare, plus a back-up *Mechanical Law*.

Normal law

Normal Law differs depending on the stage of flight. These include:

- Stationary at the gate
- Taxiing from the gate to a runway or from a runway back to the gate
- Beginning the take-off roll
- Initial climb
- Cruise climb and cruise flight at altitude
- Final descent, flare and landing.

Normal Law is different depending on the stage of flight. During the transition from take-off to cruise there is a 5 second transition, from descent to flare there is a two second delay and from flare to ground there is another 2 second transition in *Normal Law*.

Ground mode

The aircraft behaves as in direct mode: The autotrim feature is turned off and there is a direct response of the elevators to control column (or sidestick on Airbus) inputs. The horizontal stabilizer is set to 4° up but manual settings (e.g. for center of gravity) override this setting. After the wheels leave the ground, a 5 second transition occurs where *Normal Law - flight mode* takes over from ground mode.

Flight mode

The flight mode of *Normal Law* provides five types of protection: Pitch attitude, load factor limitations, high speed, high-AOA and bank angle. Flight mode is operational from take-off to 100 feet above the ground, but can be lost as a result of pilot commands or system failures. Loss of *Normal Law* as a result of a system failure results in *Alternate Law 1* or *2*.

Unlike conventional controls, in *Normal Law flight mode* the sidestick provides a load factor proportional to stick deflection which is independent of aircraft speed. When the stick is neutral and the load factor is 1g the aircraft remains in level flight without the pilot changing the elevator trim. The aircraft also maintains a proper pitch angle once a turn has been established, up to 33° bank. The system prevents further trim up when the angle of attack is excessive, the load factor exceeds 1.3g or when the bank angle exceeds 33°.

Alpha protection (α-Prot) prevents stalling and the effects of windshear. The protection engages when the angle of attack is between α-Prot and α-Max and limits the angle of attack commanded by the pilot's sidestick or, if autopilot is engaged, it disengages the autopilot.

High speed protection will automatically recover from an overspeed. There are two speed limitations for high altitude aircraft, V_{MO} (Velocity Maximum Operational) and M_{MO}

(Mach Maximum Operational) the two speeds are the same at approximately 31,000 feet, below which overspeed is determined by V_{MO} and above 31,000 feet by M_{MO}.

Flare mode

A380 in take off

This mode is automatically engaged when the radar altimeter indicates 100 feet above ground. At 50 feet the aircraft trims the nose slightly down. During the flare, *Normal Law* provides high-AOA protection and bank angle protection. The load factor is permitted to be from 2.5g to -1g, or 2.0g to 0g when slats are extended. Pitch attitude is limited to +30 to -15° which is reduced to 25° as the aircraft slows.

Alternate law

The are four reconfiguration modes for the Airbus fly-by-wire aircraft, two *Alternate Law (1 and 2)*, *Direct Law* and *Mechanical Law*. The ground mode and flare modes for *Alternate Law* are identical to those modes for *Normal Law*.

Alternate law 1 (ALT1) mode combines a *Normal Law* lateral mode with the load factor, bank angle protections retained. High angle of attack protection may be lost and low energy (level flight stall) protection is lost. High speed and high angle of attack protections enter alternative law mode.

ALT1 maybe entered if there are faults in the horizontal stabilizer, an elevator, yaw-damper actuation, slat or flap sensor, or a single air data reference fault.

Alternate law 2 (ALT2) loses *Normal Law* lateral mode (replaced by roll direct mode and yaw alternate mode) along with pitch attitude protection, bank angle protection and low energy protection. Load factor protection is retained. High angle of attack and high speed protections are retained unless the reason for *Alternate 2 Law* mode is the failure of two air-data references or if the two remaining air data references disagree.

ALT2 mode is entered when 2 engines flame out (on dual engine aircraft), faults in two inertial or air-data references, with the autopilot being lost, except with an ADR disagree. This mode may also be entered with an all spoilers fault, certain ailerons fault, or pedal transducers fault.

Direct law

Direct mode (DIR) loses normal lateral mode and all protections, the aircraft assumes *Alternate Law* yaw mode and *Direct Law* roll mode. Elevator can then only be controlled by the manual trim. Control surface motion is directly related to the sidestick and rudder pedal motion.

DIR is entered if there is failure of three inertial reference units or the primary flight computers, faults in two elevators, flame out in two engines (on a two engine aircraft) or when the captain's primary flight computer is inoperable.

Mechanical law

In the *Mechanical Law* back-up mode, pitch is controlled by the mechanical trim system and lateral direction is controlled by the rudder pedals operating the rudder mechanically.

Boeing 777 Primary Flight Control System

The cockpit of the 777 is similar to 747-400, a fly-by-wire control simulating mechanical control

The fly-by-wire electronic flight control system of the Boeing 777 differs from the Airbus EFCS. The design principle is to provide a system that responds similarly to a mechanically controlled system. Because the system is controlled electronically the flight control system can provide flight envelope protection.

The electronic system is subdivided between 2 levels, the 4 actuator control electronics (ACE) and the 3 primary flight computers (PFC). The ACEs control actuators (from those on pilot controls to control surface controls and the PFC). The role of the PFC is to calculate the control laws and provide feedback forces, pilot information and warnings.

Standard Protections and augmentations

The flight control system on the 777 is designed to restrict control authority beyond certain range by increasing the back pressure once the desired limit is reached. This is done via electronically controlled backdrive actuators (controlled by ACE). The protections and augmentations are: bank angle protection, turn compensation, stall protection, over-speed protection, pitch control, stability augmentation and thrust asymmetry compensation. The design philosophy is: "to inform the pilot that the command being given would put the aircraft outside of its normal operating envelope, but the ability to do so is not precluded."

Normal mode

In *Normal mode* the PFCs transmit actuator commands to the ACEs, which convert them into analog servo commands. Full functionality is provided, including all enhanced performance, envelope protection and ride quality features.

Secondary mode

Boeing *Secondary mode* is comparable to the Airbus *Alternate Law*, with the PFCs supplying commands to the ACEs. However, EFCS functionality is reduced, including loss of flight envelope protection. Like the Airbus system, this state is entered when a number of failures occur in the EFCS or interfacing systems (e.g. ADIRU or SAARU).

Direct mode

In *Direct mode* each ACE decodes pilot commands directly from the pilot controller transducers. This mode can be manually or automatically entered. Automatic entry occurs when there is a failure of all PFCs, ACEs, and/or loss of a control data bus.

Chapter 3

Variometer & Machmeter

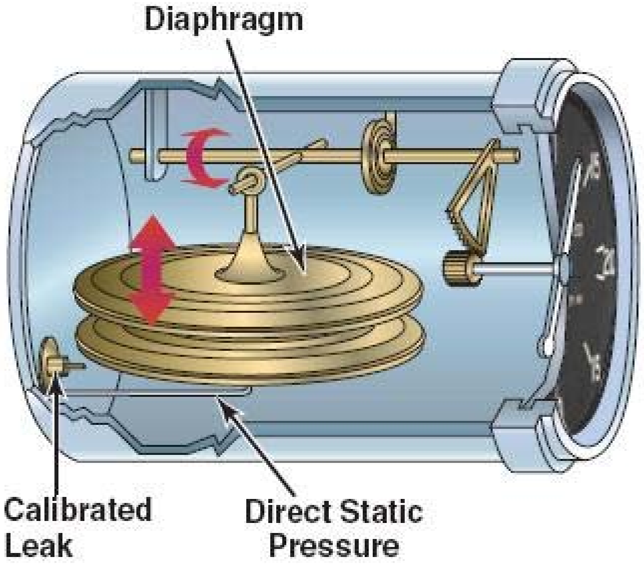
Variometer

A **variometer** (also known as a **rate of climb and descent Indicator (RCDI)**, **rate-of-climb indicator**, **vertical speed indicator (VSI)**, or **vertical velocity indicator (VVI)**) is one of the flight instruments in an aircraft used to inform the pilot of the near instantaneous (rather than averaged) rate of descent or climb. It can be calibrated in knots, feet per minute (101.333 ft/min = 1 kn) or metres per second, depending on country and type of aircraft.

In powered flight the pilot makes frequent use of the **VSI** to ascertain that level flight is being maintained, especially during turning manoeuvres. In gliding, the instrument is used almost continuously during normal flight, often with an audible output, to inform the pilot of rising or sinking air. It is usual for gliders to be equipped with more than one type of variometer. The simpler type does not need an external source of power and can therefore be relied upon to function regardless of whether a battery or power source has been fitted. The electronic type with audio needs a power source to be operative during the flight. The instrument is of little interest during launching and landing, with the exception of aerotow, where the pilot will usually want to avoid releasing in sink.

Variometer for Paragliders, Hang Gliders and Ballooneers

Description



Schematic drawing of the internals of a classic aircraft variometer

Variometers measure the rate of change of altitude by detecting the change in air pressure (static pressure) as altitude changes. A simple variometer can be constructed by adding a large reservoir (a thermos bottle) to augment the storage capacity of a common aircraft rate-of-climb instrument. In its simplest electronic form, the instrument consists of an air bottle connected to the external atmosphere through a sensitive air flow meter. As the aircraft changes altitude, the atmospheric pressure outside the aircraft changes and air flows into or out of the air bottle to equalise the pressure inside the bottle and outside the aircraft. The rate and direction of flowing air is measured by the cooling of one of two self-heating thermistors and the difference between the thermistor resistances will cause a voltage difference; this is amplified and displayed to the pilot. The faster the aircraft is ascending (or descending), the faster the air flows. Air flowing out of the bottle indicates that the altitude of the aircraft is increasing. Air flowing into the bottle indicates that the aircraft is descending.

Newer variometer designs directly measure the static pressure of the atmosphere using a pressure sensor and detect changes in altitude directly from the change in air pressure instead of by measuring air flow. These designs tend to be smaller as they do not need the air bottle. They are more reliable as there is no bottle to be affected by changes in temperature and less chances for leaks to occur in the connecting tubes.

The designs described above, which measure the rate of change of altitude by automatically detecting the change in static pressure as the aircraft changes altitude are referred to as "uncompensated" variometers. The term "vertical speed indicator" or "VSI" is most often used for the instrument when it is installed in a powered aircraft. The term "variometer" is most often used when the instrument is installed in a glider or sailplane.

An "Inertia lead" VSI or ILVSI compensates for relative "*g*" forces experienced in a turn (powered aircraft) and provides appropriate mechanical compensation to remove otherwise erroneous indications of climb or descent.

Panel mounted variometer for gliders

Purpose

Human beings, unlike birds and other flying animals, are not able directly to sense climb and sink rates. Before the invention of the variometer, sailplane pilots found it very hard to soar. Although they could readily detect abrupt *changes* in vertical speed ("in the seat of the pants"), their senses did not allow them to distinguish lift from sink, or strong lift from weak lift. The *actual* climb/sink rate could not even be guessed at, unless there was some clear fixed visual reference nearby. Being near a fixed reference means being near to a hillside, or to the ground. Except when hill-soaring (exploiting the lift close to the up-wind side of a hill), these are generally very unprofitable positions for glider pilots to be in. The most useful forms of lift (thermal and wave lift) are found at higher altitudes and it is very hard for a pilot to detect or exploit them without the use of a variometer.

After the variometer was invented in 1929 by Alexander Lippisch and Robert Kronfeld, the sport of gliding moved into a new realm.

The vertical speed indicator from a Robinson R22

Total energy compensation

As the sport developed, however, it was found that these very simple "uncompensated" instruments had their limitations. The information that glider pilots really need to soar is the vertical speed of the glider in isolation of stick thermals, i.e., in isolation of changes in altitude due exclusively to changes in speed.

When the pilot chooses to pull up to enter a thermal or to dive to exit a sink area, an uncompensated variometer will include the change in altitude due to the change in velocity in its read-out, thus marring the airmass' climb or sink rate. Therefore an uncompensated variometer can only accurately indicate the vertical speed of the airmass when flying at constant speed.

The action of diving or pulling up affects the speed of the sailplane. A sailplane can exchange height for speed or speed for height, i.e. potential energy for kinetic energy or kinetic energy for potential energy. In fact, in still air, the sum of potential energy and kinetic energy, i.e., the *Total Energy*, remains constant (neglecting energy loss due to drag), hence the name *Total Energy compensation*.

Most modern sailplanes are equipped with *Total Energy compensated* variometers.

Total energy compensation in theory

While the driving principle is:

1. Potential Energy + Kinetic Energy = Total Energy

the compensation to cancel stick thermals is:

2. Potential Energy **Gained** = Kinetic Energy **Lost** (*stick thermal*)

i.e.:

3. $\Delta E_{pot} = -\Delta E_{kin}$

or

4. $\Delta E_{pot} + \Delta E_{kin} = 0$

Since

5. Potential Energy is proportional to Height ($E_{pot} \propto h$)

and

6. Kinetic Energy is proportional to Velocity squared ($E_{kin} \propto v^2$),

then from (3):

7. $\Delta h \propto -\Delta(v^2)$

where

8. Δh is the compensation to apply to the uncompensated variometer reading.

The Vertical Speed Indicator in this Van's RV-4 light aircraft is on the top row, on the right.

Total energy compensation in practice

In most sailplanes, total energy compensation is achieved by connecting the variometer to the atmosphere via a "total energy probe", that produces vacuum proportional to the square of the glider's air speed - in effect, a negative pitot. Alternatively, the subtraction may be done electronically by the flight computer based on indicated airspeed (pitot).

Very few powered aircraft have total energy variometers. The pilot of a powered aircraft is more interested in the true rate of change of altitude, as he often wants to hold a constant altitude or maintain a steady climb or descent.

The total energy probe used to be shaped as a classical venturi (two small funnels connected back-to-back by their narrow ends), or nowadays the Irving Tube - a slot or pair of holes on the back side of a quarter inch vertical tube. The geometry of the total energy probe is such that air flow generates suction (reduced pressure).

To maximise the precision of this compensation effect, the total energy probe needs to be in undisturbed airflow ahead of the aircraft nose or tail fin (the "Braunschweig tube", the long cantilevered tube with a kink in the end that can be seen projecting from the leading edge of the tail fin on most modern sailplanes.)

Netto variometer

A second type of compensated variometer is the **Netto** or **airmass** variometer. In addition to TE compensation, the Netto variometer adjusts for the intrinsic sink rate of the glider at a given speed (the polar curve) adjusted for the wing loading due to water ballast. The Netto variometer will always read zero in still air. This provides the pilot with the accurate measurement of air mass vertical movement critical for final glides.

The **Relative Netto Variometer** indicates the vertical speed the glider would achieve IF it flies at thermalling speed - independent of current air speed and attitude. This reading is calculated as the Netto reading minus the glider's minimum sink.

When the glider circles to thermal, the pilot needs to know the glider's vertical speed instead of that of the air mass. The **Relative Netto Variometer** (or sometimes the **super Netto**) includes a g-sensor to detect thermalling.

When thermalling, the sensor will detect acceleration (gravity plus centrifugal) above 1 g and tell the relative netto variometer to stop subtracting the sailplane's wing load-adjusted polar sink rate for the duration. Some earlier nettos used a manual switch instead of the g sensor.

Electronic variometers

In modern gliders, most electronic variometers generate a sound whose pitch and rhythm depends on the instrument reading. Typically the audio tone increases in frequency as the variometer shows a higher rate of climb and decreases in frequency towards a deep groan as the variometer shows a faster rate of descent. When the variometer is showing a climb, the tone is often chopped, while during a descent the tone is not chopped and the rate of chopping may be increased as the climb rate increases. The vario is typically silent in still air or in lift which is weaker than the typical sink rate of the glider at minimum sink. This audio signal allows the pilot to concentrate on the external view instead of having to watch the instruments, thus improving safety and also giving the pilot more opportunity to search for promising looking clouds and other signs of lift. A variometer that produces this type of audible tone is known as an "audio variometer".

Advanced electronic variometers in gliders can present other information to the pilot from GPS receivers. The display can thus show the bearing, distance and height required to reach an objective. In cruise mode (used in straight flight), the vario can also give an audible indication of the correct speed to fly depending on whether the air is rising or sinking. The pilot merely has to input the estimated MacCready setting, which is the expected rate of climb in the next acceptable thermal.

There is an increasing trend for advanced variometers in gliders which tend towards flight computers and present other information such as controlled airspace, lists of turnpoints and even collision warnings. Some will also store positional GPS data during the flight for later analysis.

Radio controlled soaring

Variometers are also used in radio controlled gliders. Typically it takes the form of a radio transmitter in the plane, and a receiver held by the pilot on the ground. Depending on the design, the receiver may give the pilot the current altitude of the plane (an altimeter) and some sort of display that indicates if the plane is gaining or losing altitude—often via a tone just like in full scale gliders. Other forms of telemetry may also be provided by the system, giving things such as airspeed and battery voltage. Varios used in radio controlled planes may or may not feature total energy compensation (the better/more expensive ones generally do.)

Variometers are strictly optional for R/C glider use—a skilled pilot can generally determine if their plane is going up or down via visual cues alone, and so the use of a variometer is often seen as a `crutch', as a replacement for skill, and many pilots prefer not to use them at all, as the tone can be distracting, and the (usually small) amount of weight added to the plane does affect performance. The use of variometers is permitted in some R/C soaring contests and prohibited in others.

Perhaps the most popular brands of R/C variometers are the Picolario and the WsTech CS Voice.

Machmeter

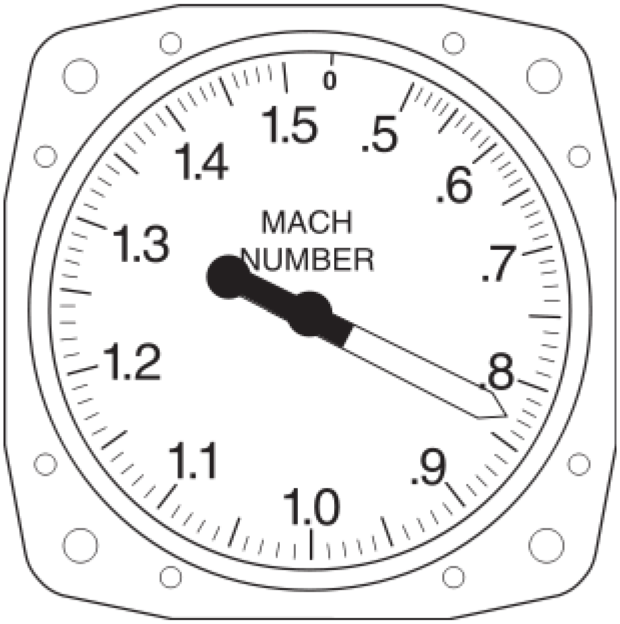


Illustration showing the face of a Machmeter reading a Mach number of 0.83

A **Machmeter** is an aircraft pitot-static system flight instrument that shows the ratio of the true airspeed to the speed of sound, a dimensionless quantity called Mach number. This is shown on a Machmeter as a decimal fraction. An aircraft flying at the speed of sound is flying at a Mach number of one, expressed as *Mach 1*.

Use

As an aircraft in transonic flight approaches the speed of sound, it first reaches its critical mach number, where air flowing over low-pressure areas of its surface locally reaches the speed of sound, forming shock waves. The indicated airspeed for this condition changes with ambient pressure, which in turn changes with altitude. Therefore, indicated airspeed is not entirely adequate to warn the pilot of the impending problems. Mach number is more useful, and most high-speed aircraft are limited to a maximum operating Mach number, also known as $\mathbf{M_{MO}}$.

For example, if the $\mathbf{M_{MO}}$ is Mach 0.83, then at 30,000 feet (9,144 m) where the speed of sound under standard conditions is 590 knots (1,093 km/h; 679 mph), the true airspeed at M_{MO} is 489 knots (906 km/h; 563 mph). The speed of sound increases with air temperature, so at Mach 0.83 at 10,000 feet (3,048 m) where the air is much warmer than at 30,000 feet (9,144 m), the true airspeed at M_{MO} would be 530 knots (982 km/h; 610 mph).

Operation

Some older mechanical Machmeters use an altitude aneroid and an airspeed capsule which together convert pitot-static pressure into Mach number. Modern electronic Machmeters use information from an air data computer system.

Calibration

In subsonic flow the Mach meter can be calibrated according to:

$$M = \sqrt{5\left[\left(\frac{q_c}{P} + 1\right)^{\frac{2}{7}} - 1\right]}$$

where:

M is Mach number
q_c is impact pressure and
P is static pressure
and assuming the ratio of specific heats is 1.4

When a shock wave forms across the pitot tube the required formula is derived from the Rayleigh Supersonic Pitot equation, and is solved iteratively:

$$M = 0.88128485\sqrt{\left[\left(\frac{q_c}{P}+1\right)\left(1-\frac{1}{[7M^2]}\right)^{\frac{5}{2}}\right]}$$

where:

q_c is now impact pressure measured behind a normal shock.

Note that the inputs required are impact pressure (or total pressure) and static pressure. Air temperature input is not required

Chapter 4

Attitude Indicator & Heading Indicator

Attitude Indicator

Attitude indicator with integrated localizer and glideslope indicators, earth below (brown) and sky above (blue) it's perfectly level and not turning, possibly in a slight dive/descent.

An **attitude indicator** (AI), also known as **gyro horizon** or **artificial horizon**, is an instrument used in an aircraft to inform the pilot of the orientation of the aircraft relative to earth. It indicates pitch (fore and aft tilt) and bank or **roll** (side to side tilt) and is a primary instrument for flight in instrument meteorological conditions. Attitude indicators also have significant application under visual flight rules, though some light aircraft do not have them installed.

Use

The essential components of the indicator are:

- "miniature wings", horizontal lines with a dot between them representing the actual wings and nose of the aircraft.
- the center horizon bar separating the two halves of the display, with the top half usually blue in color to represent sky and the bottom half usually dark to represent earth.
- degree marks representing the bank angle. They run along the rim of the dial. On a typical indicator, the first 3 marks on both sides of the center mark are 10 degrees apart. The next is 60 degrees and the mark in the middle of the dial is 90 degrees.

If the symbolic aircraft dot is above the horizon line (blue background) the aircraft is nose up. If the symbolic aircraft dot is below the horizon line (brown background) the aircraft is nose down. When the dot and wings are on the horizon line, the aircraft is in level flight. Because it is the horizon that moves up and down and turns, while the symbolic aircraft is fixed relative to the rest of the instrument panel, trainees get confused; a standard corrective given by flight instructors is "Fly the little airplane, not the horizon."

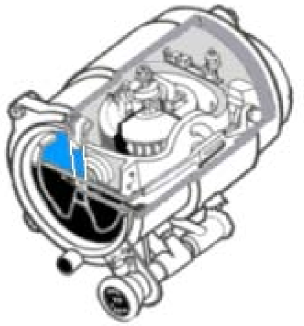
A 45 degree turn is approximated by placing the indicator equidistant between the 30 and 60 degree marks.

The pitch angle is relative to the ground, which is not as helpful as knowing the angle of attack of the wing, a much more critical measure of performance. The pilot must infer the total performance by using other instruments such as the airspeed indicator, altimeter, vertical speed indicator, and power instruments, e.g. an engine tachometer.

Most Russian-built aircraft have a somewhat different design. The background display is colored as in a Western instrument, but moves up and down only to indicate pitch. A symbol representing the aircraft (which is fixed in a Western instrument) rolls left or right to indicate bank angle.

It was proposed that a hybrid version of the Western and Russian artificial horizon systems to be developed that would be more intuitive than either.

Operation



Schematics drawing of the insides of a classic attitude indicator

Attitude indicators use a gyroscope (powered via vacuum pump or electrical motor) to establish an inertial platform. The gyroscope is geared to a display that has two dimensions of freedom, simultaneously displaying pitch and bank. The display may be colored to indicate the horizon as the division between the two colored segments (typically blue for sky and brown for ground), and is intended to be intuitive to use. The actual bank angle is calibrated around the circumference of the instrument. The pitch angle is indicated by a series of calibration lines, each representing 5° or 10° of pitch depending on design. The Artificial Horizon has turning errors when turning through 090 and 270 degrees, and it has no turning errors when turning through 180 and 000 degrees. For example, when turning through 090 degrees the Artificial Horizon will show nose up and bank angle too low. When turning through 180 degrees it will show nose up and bank angle correct.

Some attitude indicators can only tolerate a specific range of bank angles. If the aircraft rolls too steeply — while performing aerobatics, for example — the attitude indicator can "tumble" and become temporarily unusable. For this reason, some attitude indicators are fitted with a "cage" (a device to restore the gyroscope to an erect position). Most modern attitude indicators slowly re-erect back to level after a tumble. Others do not tumble at all.

AHRS are able to provide three-axis information that can be shared with multiple devices in the aircraft, such as "glass cockpit" primary flight displays (PFDs). AHRS have been proven to be highly reliable and are in wide use in commercial and business aircraft. Recent advances in MEMS manufacturing have brought the price of FAA-certified AHRS down to less than $15,000, making them practical for general aviation aircraft.

With most AHRS systems, if an aircraft's AIs have failed there will be a standby AI located in the center of the instrument panel, where other standby basic instruments such as the airspeed indicator and the attitude indicator are also available. These mostly mechanical standby instruments may be available even if the electronic flight instruments fail, though the standby attitude indicator is electrically driven and will, after a short time, fail if electrical power to it fails.

Heading Indicator

A heading indicator in a small aircraft.

The **heading indicator** (also called an **HI**) is a flight instrument used in an aircraft to inform the pilot of the aircraft's heading. It is sometimes referred to by its older names, the **directional gyro** or **DG**, and also (UK usage) **direction indicator** or **DI**.

Use

The primary means of establishing the heading in most small aircraft is the magnetic compass, which, however, suffers from several types of errors, including that created by the 'dip' or downward slope of the earth's magnetic field. Dip error causes the magnetic compass to read incorrectly whenever the aircraft is in a bank, or during acceleration, making it difficult to use in any flight condition other than perfectly straight and level. To remedy this, the pilot will typically maneuver the airplane with reference to the heading indicator, as the gyroscopic heading indicator (HI) is unaffected by dip and acceleration errors. The pilot will periodically reset the HI to the heading shown on the magnetic compass.

Operation

The DG works using a gyroscope, tied to the aircraft horizontal, to establish an inertial platform. As such any configuration of the aircraft horizontal which does not match the local earth horizontal results in gimbal error (essentially leading to a variation in the predictable 'apparent' wander known in this instance as drift.) The HI is arranged so that only the horizontal axis is used to drive the display, which consists of a circular compass card calibrated in degrees. The gyroscope is spun either electrically, or using air from a vacuum pump (sometimes a pressure pump in high altitude aircraft) driven from the aircraft's engine. Because the earth rotates (ω, 15° per hour), and because of small accumulated errors caused by friction and imperfect balancing of the gyro, the HI will drift over time, and must be reset from the compass periodically. The apparent drift is predicted by **ω sin Latitude** and will thus be greatest over the poles. Another sort of apparent drift exist in the form of transport wander, where aircraft movement will essentially add or subtract to the effect of the earth's rotation upon a gyroscope. To counter for the effect of earth rate drift a latitude nut can be set (on the ground only) which induces a (hopefully equal and opposite) real wander in the gyroscope. Normal procedure is to realign the direction indicator once each ten to fifteen minutes during routine in-flight checks. Failure to do this is a common source of navigation errors among new pilots.

Variations

Some more expensive heading indicators are 'slaved' to a sensor (called a 'flux gate'). The flux gate continuously senses the earth's magnetic field, and a servo mechanism constantly corrects the heading indicator. These 'slaved gyros' reduce pilot workload by eliminating the need for manual realignment every ten to fifteen minutes.

The prediction of drift in degrees per hour, is as follows:

SOURCE	Drift Rate (Degrees per Hour)	Sign (Northern Hemisphere)	Sign (Southern Hemisphere)
Earth Rate	15 * sin Mean Operating Latitude	- (causing an under-read)	+ (causing an over-read)
Latitude Nut	15 * sin Latitude of Setting	+	-
Transport Wander EAST	(East Groundspeed Component (or sine track angle x groundspeed or change in longitude/flight time in hours) * tan Mean Operating Latitude)/60	-	+
Transport Wander WEST	(West Groundspeed Component (or sine track angle x groundspeed or change in longitude/flight time in hours) * tan Mean Operating Latitude)/60	+	-
Real/Random Wander	As given in the Aircraft Operating Manual	As given	As given

Although it is possible to predict the drift, there will be minor variations from this basic model, accounted for by gimbal error (operating the aircraft away from the local horizontal), among others. A common source of error here is the improper setting of the latitude nut (to the opposite hemisphere for example). The table however allows one to gauge whether an indicator is behaving as expected, and as such, is compared with the realignment corrections made with reference to the magnetic compass. Transport wander is an undesirable consequence of apparent drift.

Chapter 5

Turn Coordinator & Turn Indicator

Turn Coordinator

Image showing the face of a turn coordinator during a standard rate coordinated right turn.

The **turn coordinator** (TC) is a flight instrument which displays to a pilot information about the rate of yaw (turn), roll, and the coordination of the turn. The turn coordinator was developed to replace the older turn and bank indicator, which displayed rate and quality of turn but not rate of roll.

History

The turn coordinator was initially developed as a single instrument used by autopilots to control the roll axis of an aircraft. The turn coordinator without autopilot sensing became popular in general aviation airplanes largely because of the newer look. The turn coordinator rarely appeared in jets or large airplanes.

Use

The indicator includes a miniature airplane as seen from behind. When the miniature airplane wings are level, the yaw rate plus the roll rate is zero. When the wings are not level, the amount and direction of tilt indicates the rate of turn plus the rate of roll. The indicator includes hash marks to indicate "wings level" flight and standard rate turns of 3° per second.

Coordinated turn

Skid

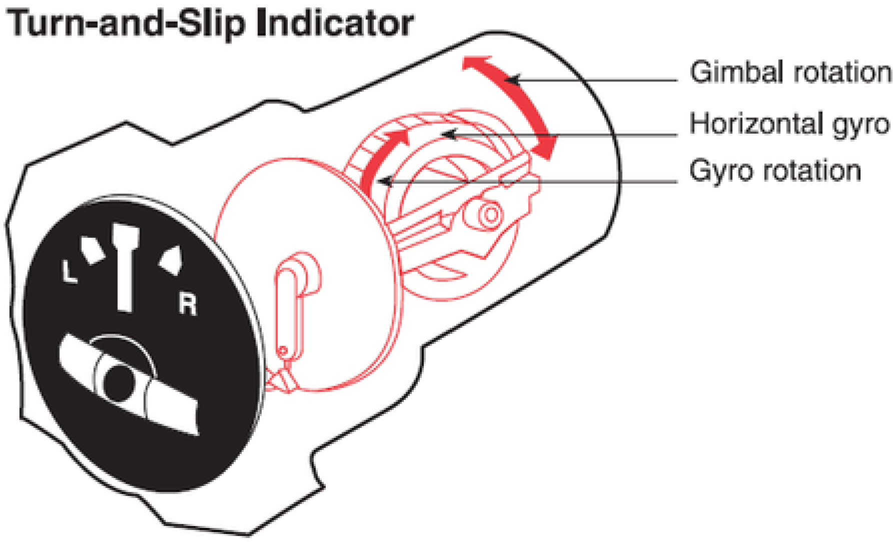
Slip

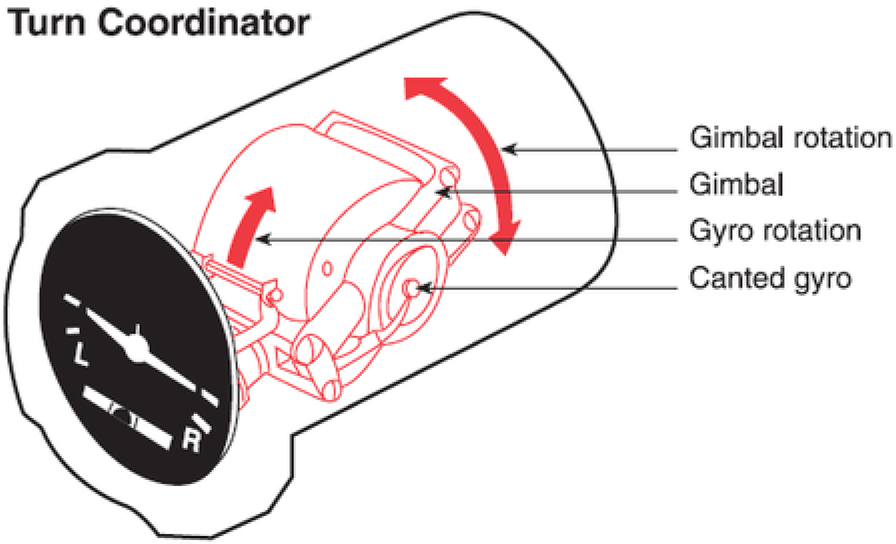
The ball inside the curved tube indicates the degree of coordination between two primary flight controls (aileron and rudder). The position of the ball indicates coordinated flight, slip or skid.

A pilot corrects for uncoordinated flight with inputs to the rudder. During a coordinated turn, the ball will remain centered. Ball deflection in the direction of the turn indicates insufficient rudder input resulting in a slip. Ball deflection opposite the direction of the turn indicates excessive rudder input resulting in a skid. The mnemonic device *"step on the ball"* aids the pilot to remember which rudder pedal requires additional pressure to return the aircraft to coordinated flight.

Unlike an attitude indicator, the turn coordinator indicates only yaw rate and roll. The attitude indicator indicates pitch and roll. To avoid confusion, some turn coordinators are marked *"No pitch information"* on the face.

Operation





Graphic of a turn and bank indicator and a turn coordinator

The turn coordinator is a gyroscopic instrument. An internal gyroscope spins at approximately 20,000 rpm with the spin axis perpendicular to the longitudinal axis of the airplane and the free axis tilted up 30° from it. As the aircraft rotates about the yaw or roll axis, the principle of gyroscopic inertia causes the gyro to resist the change in its rotational axis about the free axis. This resisting force works against a spring; thus, a slow rate of turn deflects the gyro slightly while a higher rate of roll or yaw deflects it more. The gimbal is linked to the indicator dial on which is the rear view of the miniature airplane.

The quality of turn is indicated by an inclinometer ball located below the miniature airplane. The inclinometer consists of a glass tube filled with kerosene, and a dense ball. The tube is curved such that its center is the lowest point. Normally, the ball will then sit in the center position of the tube, which represents a 'coordinated' turn. This position is marked by two vertical wires on the tube. The ball is said to be 'centered' when it sits perfectly evenly between the two wires.

Variations

The turn coordinator differs from the older turn and bank indicator in that the turn coordinator has the gyro mounted at a 30° tilt. This allows the turn coordinator to respond to roll as well as turn. The TC indication represents a sum of the roll rate and the yaw rate so it responds more quickly at the beginning and end of a turn than a turn and bank indicator. Pilots who are unfamiliar with this principle sometimes have difficulty using the turn coordinator properly, as they may see a roll indication and interpret it as a rate of turn.

The turn coordinator should be used as a performance instrument when the attitude indicator has failed. Called "partial panel" operations, this can be unnecessarily difficult or even impossible if either the pilot does not understand that the instrument is showing roll rates at some times and turn rates at others, or the internal dashpot is worn out. In the latter case the instrument is said to be underdamped; in turbulence it will indicate large full-scale deflections to the left and right, all of which are roll rate responses. In this condition it may not be possible for the pilot to maintain control of the aircraft in partial-panel operations in instrument meteorological conditions. For this and other reasons many highly experienced pilots prefer the "older" turn and bank indicator design.

Turn Indicator

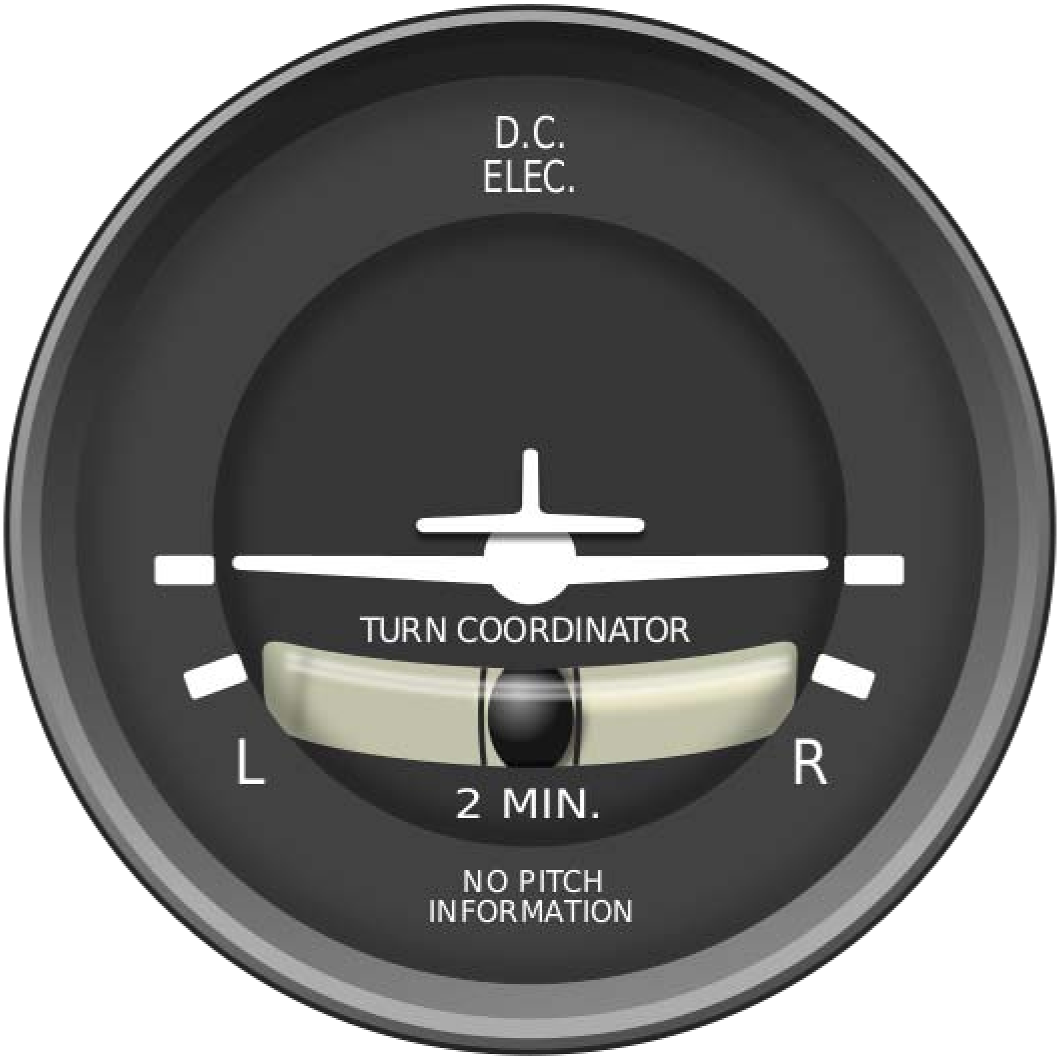
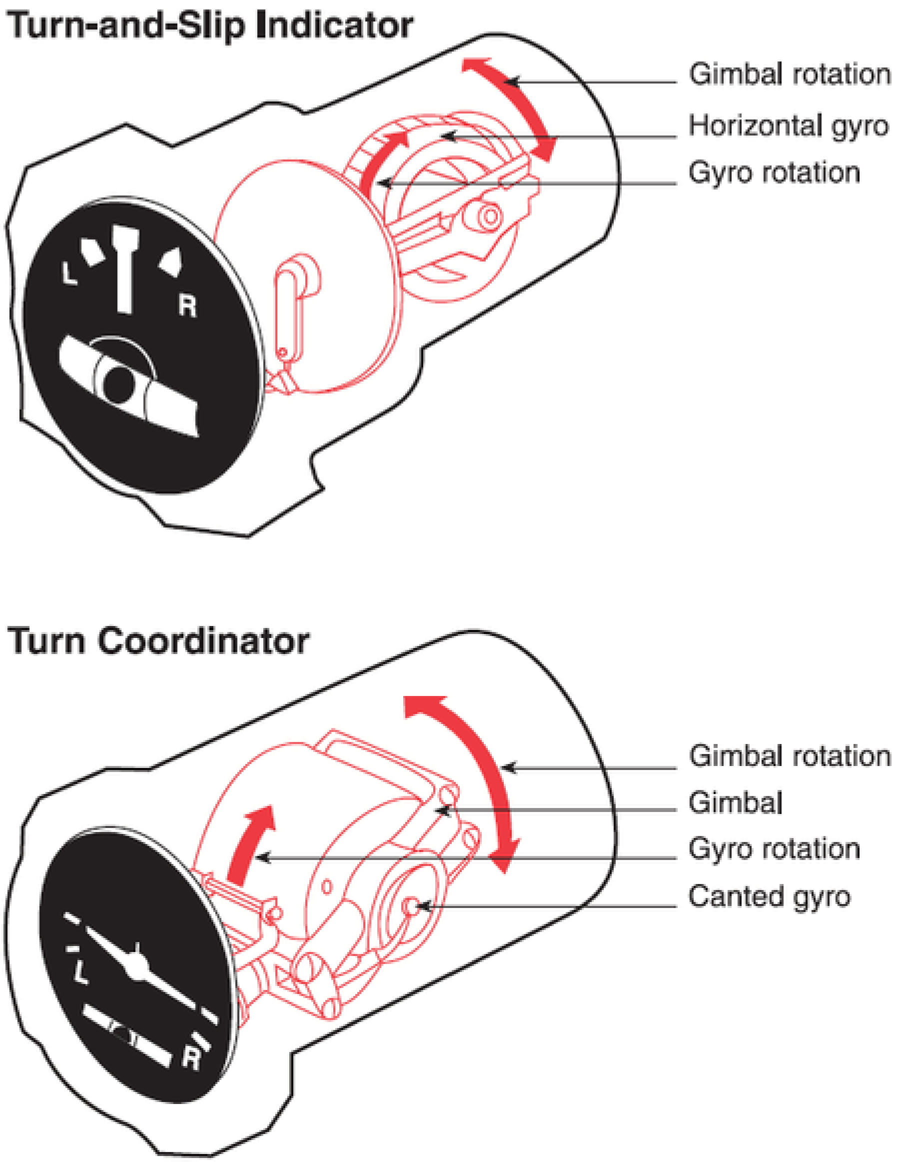


Diagram of a turn indicator.

A **turn indicator** is an aircraft flight instrument that shows the rate of turn. It is used by the pilot to maintain control when flying under Instrument flight rules.

Types



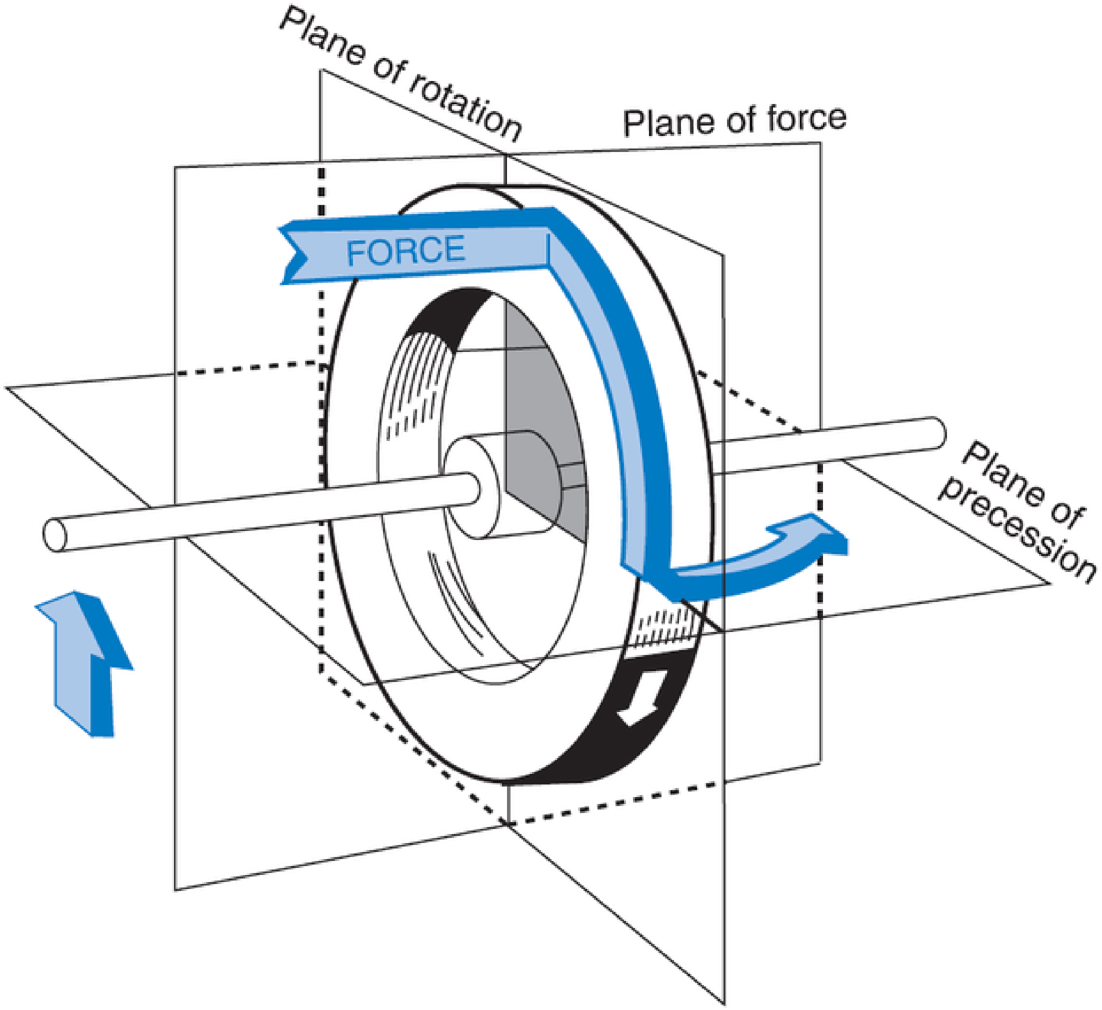
The rate gyro in a turn-and-slip indicator and turn coordinator.

The first gyroscopic aircraft instrument was the **turn and bank indicator** (also known as **turn indicator in the needle and ball**, or more recently **turn and slip indicator**).

The major limitation of this instrument is that it senses rotation only about the vertical axis of the aircraft. It tells nothing of the rotation around the longitudinal axis, which in normal flight occurs before the aircraft begins to turn.

The **turn coordinator** was created to overcome this problem by having its gimbal frame angled upward about 30° from the longitudinal axis of the aircraft. This allows it to sense both roll and yaw.

Use and operation



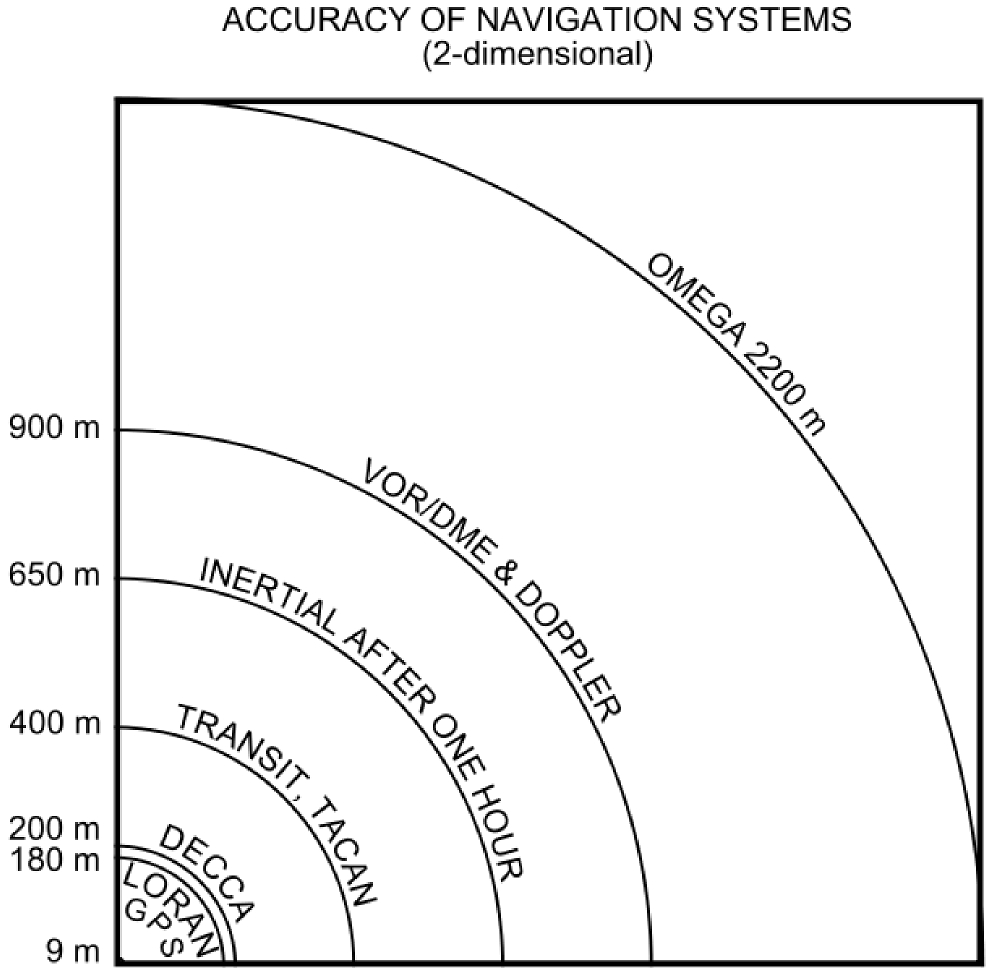
Precession causes a force applied to a spinning wheel to be felt 90° from the point of application in the direction of rotation.

The dial of these instruments is usually marked "2 min. turn", although some turn-and-slip indicators used in faster aircraft like the Concorde are marked "4 min. turn". In gliders, the calibration spring is usually set for a one-minute standard rate turn. A standard-rate turn is being made whenever the needle aligns with a turn marking ("doghouse").

Both instruments incorporate an inclinometer-like indicator, which is either a pendulum or a black glass ball sealed inside a curved glass tube that is partially filled with a liquid similar to the fluid used in a compass. This ball measures the relative strength of the force of gravity and the force of inertia caused by a turn. When the aircraft is flying straight-and-level, there is no inertia acting on the ball, and it remains in the center of the tube between two wires. In a turn made with a bank angle that is too steep, the force of gravity is greater than the inertia and the ball rolls down to the inside of the turn. If the turn is made with too shallow a bank angle, the inertia is greater than gravity and the ball rolls upward to the outside of the turn. The ball does not indicate the amount of bank, neither is it limited to an indication of slip; it only indicates the relationship between the angle of bank and the rate of yaw.

Chapter 6

Inertial Navigation System



An **inertial navigation system** (INS) is a navigation aid that uses a computer, motion sensors (accelerometers) and rotation sensors (gyroscopes) to continuously calculate via dead reckoning the position, orientation, and velocity (direction and speed of movement) of a moving object without the need for external references. It is used on vehicles such as ships, aircraft, submarines, guided missiles, and spacecraft. Other terms used to refer to inertial navigation systems or closely related devices include **inertial guidance system**, **inertial reference platform**, **inertial instrument**, and many other variations.

Overview

An inertial navigation system includes at least a computer and a platform or module containing accelerometers, gyroscopes, or other motion-sensing devices. The INS is initially provided with its position and velocity from another source (a human operator, a GPS satellite receiver, etc.), and thereafter computes its own updated position and velocity by integrating information received from the motion sensors. The advantage of an INS is that it requires no external references in order to determine its position, orientation, or velocity once it has been initialized.

An INS can detect a change in its geographic position (a move east or north, for example), a change in its velocity (speed and direction of movement), and a change in its orientation (rotation about an axis). It does this by measuring the linear and angular accelerations applied to the system. Since it requires no external reference (after initialization), it is immune to jamming and deception.

Inertial-navigation systems are used in many different moving objects, including vehicles—such as aircraft, submarines, spacecraft—and guided missiles. However, their cost and complexity place constraints on the environments in which they are practical for use.

Gyroscopes measure the angular velocity of the system in the inertial reference frame. By using the original orientation of the system in the inertial reference frame as the initial condition and integrating the angular velocity, the system's current orientation is known at all times. This can be thought of as the ability of a blindfolded passenger in a car to feel the car turn left and right or tilt up and down as the car ascends or descends hills. Based on this information alone, he knows what direction the car is facing but not how fast or slow it is moving, or whether it is sliding sideways.

Accelerometers measure the linear acceleration of the system in the inertial reference frame, but in directions that can only be measured relative to the moving system (since the accelerometers are fixed to the system and rotate with the system, but are not aware of their own orientation). This can be thought of as the ability of a blindfolded passenger in a car to feel himself pressed back into his seat as the vehicle accelerates forward or pulled forward as it slows down; and feel himself pressed down into his seat as the vehicle accelerates up a hill or rise up out of his seat as the car passes over the crest of a hill and begins to descend. Based on this information alone, he knows how the vehicle is accelerating relative to itself, that is, whether it is accelerating forward, backward, left, right, up (toward the car's ceiling), or down (toward the car's floor) measured relative to the car, but not the direction relative to the Earth, since he did not know what direction the car was facing relative to the Earth when he felt the accelerations.

However, by tracking both the current angular velocity of the system and the current linear acceleration of the system measured relative to the moving system, it is possible to determine the linear acceleration of the system in the inertial reference frame. Performing integration on the inertial accelerations (using the original velocity as the initial conditions) using the correct kinematic equations yields the inertial velocities of the system, and integration again (using the original position as the initial condition) yields the inertial position. In our example, if the blindfolded passenger knew how the car was pointed and what its velocity was before he was blindfolded, and if he is able to keep track of both how the car has turned and how it has accelerated and decelerated since, he can accurately know the current orientation, position, and velocity of the car at any time.

Error

All inertial navigation systems suffer from **integration drift**: small errors in the measurement of acceleration and angular velocity are integrated into progressively larger errors in velocity, which are compounded into still greater errors in position. Since the new position is calculated from the previous calculated position and the measured acceleration and angular velocity, these errors are cumulative and increase at a rate roughly proportional to the time since the initial position was input. Therefore the position must be periodically corrected by input from some other type of navigation system. The inaccuracy of a good-quality navigational system is normally less than 0.6 nautical miles per hour in position and on the order of tenths of a degree per hour in orientation.

Accordingly, inertial navigation is usually used to supplement other navigation systems, providing a higher degree of accuracy than is possible with the use of any single system. For example, if, in terrestrial use, the inertially tracked velocity is intermittently updated to zero by stopping, the position will remain precise for a much longer time, a so-called *zero velocity update*.

Control theory in general and Kalman filtering in particular, provide a theoretical framework for combining information from various sensors. One of the most common alternative sensors is a satellite navigation radio, such as GPS. By properly combining the information from an INS and the GPS system (GPS/INS), the errors in position and velocity are stable. Furthermore, INS can be used as a short-term fallback while GPS signals are unavailable, for example when a vehicle passes through a tunnel.

History

Inertial navigation systems were originally developed for rockets. American rocket pioneer Robert Goddard experimented with rudimentary gyroscopic systems. Dr. Goddard's systems were of great interest to contemporary German pioneers including Wernher von Braun. The systems entered more widespread use with the advent of spacecraft, guided missiles, and commercial airliners.

Early German World War II V2 guidance systems combined two gyroscopes and a lateral accelerometer with a simple analog computer to adjust the azimuth for the rocket in flight. Analog computer signals were used to drive four external rudders on the tail fins for flight control. The GN&C (Guidance, Navigation, and Control) system for V2 provided many innovations as an integrated platform with closed loop guidance. At the end of the war Von Braun engineered the surrender of 500 of his top rocket scientists, along with plans and test vehicles, to the Americans. They arrived at Fort Bliss, Texas in 1945 under the provisions of Operation Paperclip and were subsequently moved to Huntsville, Alabama, in 1950 where they worked for U.S. military rocket research programs.

In the early 1950s, the US government wanted to insulate itself against over dependency on the German team for military applications. Among the areas that were domestically "developed" was missile guidance. In the early 1950s the MIT Instrumentation Laboratory (later to become the Charles Stark Draper Laboratory, Inc.) was chosen by the Air Force Western Development Division to provide a self-contained guidance system backup to Convair in San Diego for the new Atlas intercontinental ballistic missile (Construction and testing were completed by Arma Division of AmBosch Arma). The technical monitor for the MIT task was a young engineer named Jim Fletcher who later served as the NASA Administrator. The Atlas guidance system was to be a combination of an on-board autonomous system, and a ground-based tracking and command system. This was the beginning of a philosophic controversy, which, in some areas, remains unresolved. The self-contained system finally prevailed in ballistic missile applications for obvious reasons. In space exploration, a mixture of the two remains.

In the summer of 1952, Dr. Richard Battin and Dr. J. Halcombe "Hal" Laning, Jr., researched computational based solutions to guidance. Dr. Laning, with the help of Phil Hankins and Charlie Werner, initiated work on MAC, an algebraic programming language for the IBM 650, which was completed by early spring of 1958. MAC became the work-horse of the MIT lab. MAC is an extremely readable language having a three-line format, vector-matrix notations and mnemonic and indexed subscripts. Today's Space Shuttle (STS) language called HAL/S, (developed by Intermetrics, Inc.) is a direct offshoot of MAC. Since the principal architect of HAL was Jim Miller, who co-authored a report on the MAC system with Hal Laning, it is probable the Space Shuttle language is named for Laning and not, as some have suggested, for the electronic star of Stanley Kubrick's *2001: A Space Odyssey"*.

Hal Laning and Richard Battin undertook the initial analytical work on the Atlas inertial guidance in 1954. Other key figures at Convair were Charlie Bossart, the Chief Engineer, and Walter Schweidetzky, head of the guidance group. Schweidetzky had worked with Wernher von Braun at Peenemuende during World War II.

The initial Delta guidance system assessed the difference in position from a reference trajectory. A velocity to be gained (VGO) calculation is made to correct the current trajectory with the objective of driving VGO to zero. The mathematics of this approach were fundamentally valid, but dropped because of the challenges in accurate inertial guidance and analog computing power. The challenges faced by the Delta efforts were overcome by the Q system of guidance. The Q system's revolution was to bind the challenges of missile guidance (and associated equations of motion) in the matrix Q. The Q matrix represents the partial derivatives of the velocity with respect to the position vector. A key feature of this approach allowed for the components of the vector cross product (v, xdv, /dt) to be used as the basic autopilot rate signals—a technique that became known as *cross-product steering*. The Q-system was presented at the first Technical Symposium on Ballistic Missiles held at the Ramo-Wooldridge Corporation in Los Angeles on June 21 and 22, 1956. The Q system was classified information through the 1960s. Derivations of this guidance are used for today's missiles.

Guidance in Human spaceflight

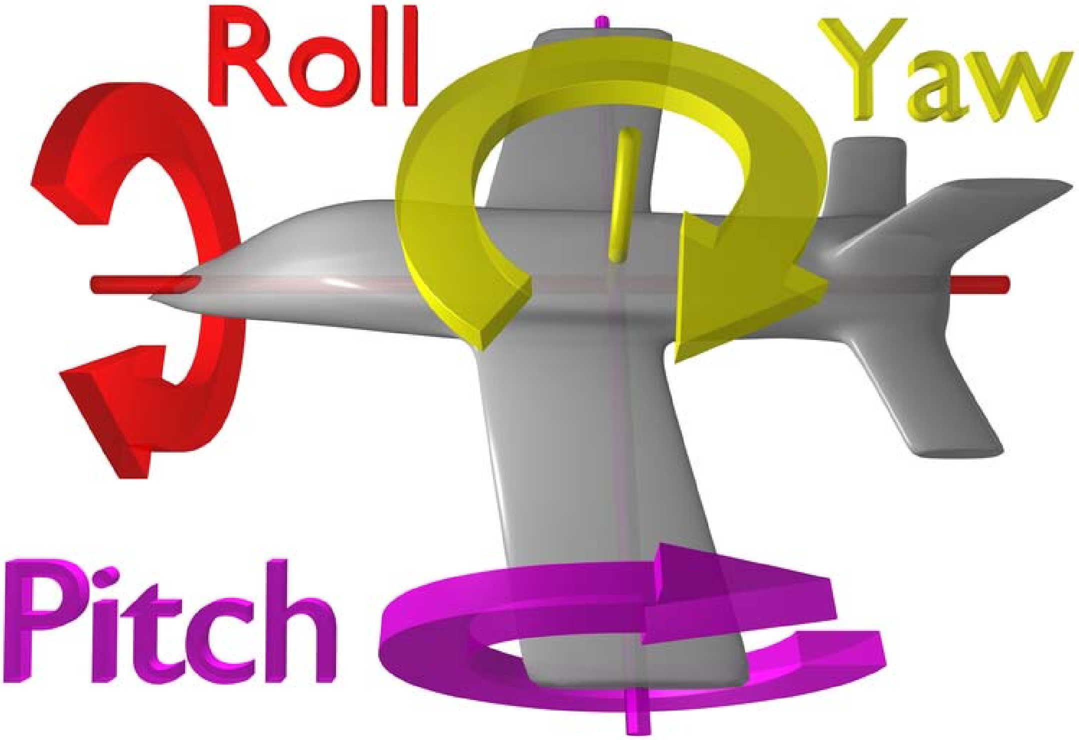
In Feb of 1961 NASA Awarded MIT a contract for preliminary design study of a guidance and navigation system for Apollo. MIT and the Delco Electronics Div. of General Motors Corp. were awarded the joint contract for design and production of the Apollo Guidance and Navigation systems for the Command Module and the Lunar Module. Delco produced the Inertial Measurement Units for these systems, Kollsman Instrument Corp. produced the Optical Systems, and the Apollo Guidance Computer was built by Raytheon under subcontract.

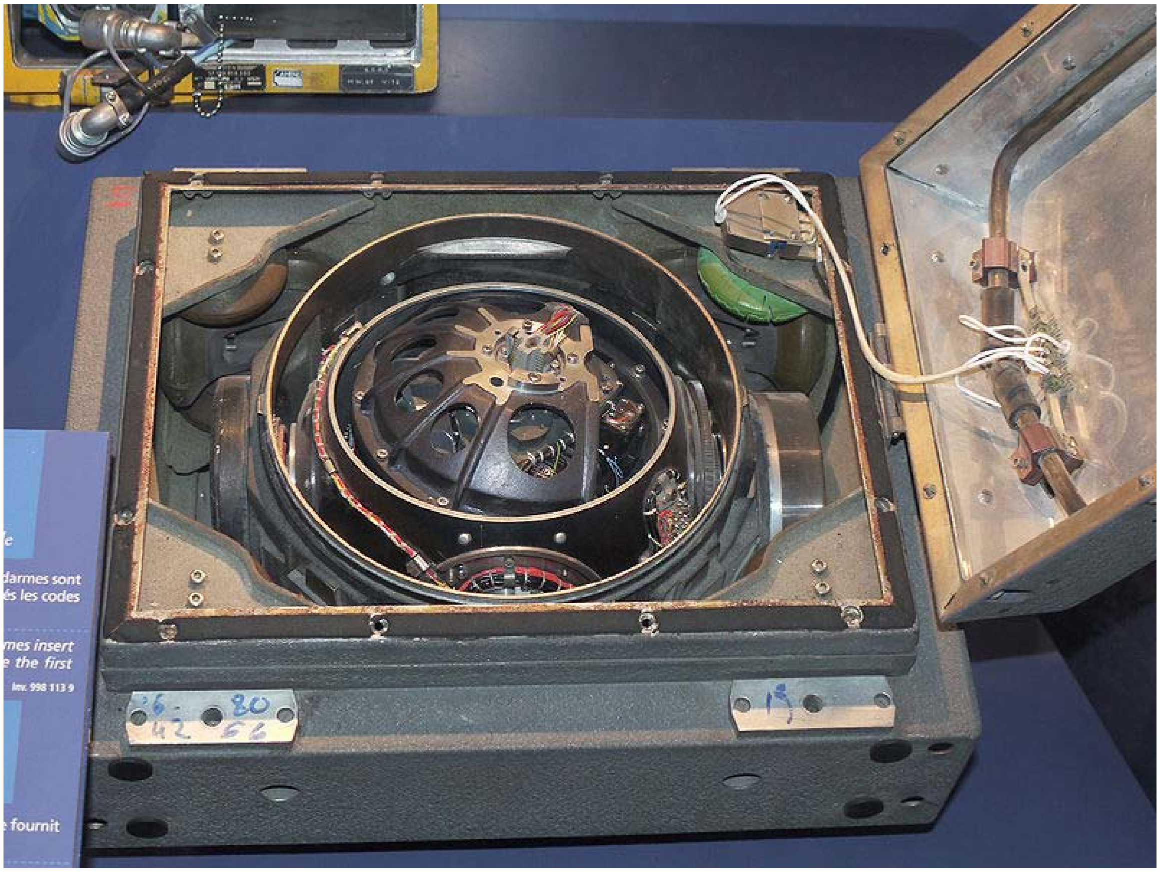
For the space shuttle, an open loop (no feedback) guidance is used to guide the shuttle from lift off until Solid Rocket Booster (SRB) separation. After SRB separation the primary space shuttle guidance is named PEG4 (Powered Explicit Guidance). PEG4 takes into account both the Q system and the predictor-corrector attributes of the original "Delta" System (PEG Guidance). Although many updates to the shuttle's navigation system have taken place over the last 30 years (ex. GPS in the OI-22 build), the guidance core of today's Shuttle GN&C system has evolved little. Within a manned system, there is a human interface needed for the guidance system. As Astronauts are the customer for the system, many new teams are formed that touch GN&C as it is a primary interface to "fly" the vehicle.

Aircraft inertial guidance

One example of a popular INS for commercial aircraft was the Delco Carousel, which provided partial automation of navigation in the days before complete flight management systems became commonplace. The Carousel allowed pilots to enter a series of waypoints, and then guided the aircraft from one waypoint to the next using an INS to determine aircraft position and velocity. Boeing Corporation subcontracted the Delco Electronics Div. of General Motors to design and build the first production Carousel systems for the early models (-100, -200, and -300) models of the 747 aircraft. The 747 utilized three Carousel systems operating in concert for reliablility purposes. The Carousel system and derivatives thereof were subsequently adopted for use in many other commercial and military aircraft. The USAF C-141 was the first military aircraft to utilize the Carousel in a dual system configuration, followed by the C-5A which utilized the triple INS configuration, similar to the 747. The KC-135 fleet was fitted with a dual Carousel system that was aided by a Doppler radar.

Inertial navigation systems in detail





Inertial navigation unit of french IRBM S3.

INSs have angular and linear accelerometers (for changes in position); some include a gyroscopic element (for maintaining an absolute angular reference).

Angular accelerometers measure how the vehicle is rotating in space. Generally, there's at least one sensor for each of the three axes: pitch (nose up and down), yaw (nose left and right) and roll (clockwise or counter-clockwise from the cockpit).

Linear accelerometers measure non-gravitational accelerations of the vehicle. Since it can move in three axes (up & down, left & right, forward & back), there is a linear accelerometer for each axis.

A computer continually calculates the vehicle's current position. First, for each of the six degrees of freedom (x,y,z and θ_x, θ_y and θ_z), it integrates over time the sensed acceleration, together with an estimate of gravity, to calculate the current velocity. Then it integrates the velocity to calculate the current position.

Inertial guidance is difficult without computers. The desire to use inertial guidance in the Minuteman missile and Project Apollo drove early attempts to miniaturize computers.

Inertial guidance systems are now usually combined with satellite navigation systems through a digital filtering system. The inertial system provides short term data, while the satellite system corrects accumulated errors of the inertial system.

An inertial guidance system that will operate near the surface of the earth must incorporate Schuler tuning so that its platform will continue pointing towards the center of the earth as a vehicle moves from place to place.

Basic schemes

Gimballed gyrostabilized platforms

Some systems place the linear accelerometers on a gimbaled gyrostabilized platform. The gimbals are a set of three rings, each with a pair of bearings initially at right angles. They let the platform twist about any rotational axis (or, rather, they let the platform keep the same orientation while the vehicle rotates around it). There are two gyroscopes (usually) on the platform.

Two gyroscopes are used to cancel gyroscopic precession, the tendency of a gyroscope to twist at right angles to an input force. By mounting a pair of gyroscopes (of the same rotational inertia and spinning at the same speed) at right angles the precessions are cancelled, and the platform will resist twisting.

This system allows a vehicle's roll, pitch, and yaw angles to be measured directly at the bearings of the gimbals. Relatively simple electronic circuits can be used to add up the linear accelerations, because the directions of the linear accelerometers do not change.

The big disadvantage of this scheme is that it uses many expensive precision mechanical parts. It also has moving parts that can wear out or jam, and is vulnerable to gimbal lock. The primary guidance system of the Apollo spacecraft used a three-axis gyrostabilized platform, feeding data to the Apollo Guidance Computer. Maneuvers had to be carefully planned to avoid gimbal lock.

Fluid-suspended gyrostabilized platforms

Gimbal lock constrains maneuvering, and it would be beneficial to eliminate the slip rings and bearings of the gimbals. Therefore, some systems use fluid bearings or a flotation chamber to mount a gyrostabilized platform. These systems can have very high precisions (e.g., Advanced Inertial Reference Sphere). Like all gyrostabilized platforms, this system runs well with relatively slow, low-power computers.

The fluid bearings are pads with holes through which pressurized inert gas (such as Helium) or oil press against the spherical shell of the platform. The fluid bearings are very slippery, and the spherical platform can turn freely. There are usually four bearing pads, mounted in a tetrahedral arrangement to support the platform.

In premium systems, the angular sensors are usually specialized transformer coils made in a strip on a flexible printed circuit board. Several coil strips are mounted on great circles around the spherical shell of the gyrostabilized platform. Electronics outside the platform uses similar strip-shaped transformers to read the varying magnetic fields produced by the transformers wrapped around the spherical platform. Whenever a magnetic field changes shape, or moves, it will cut the wires of the coils on the external transformer strips. The cutting generates an electric current in the external strip-shaped coils, and electronics can measure that current to derive angles.

Cheap systems sometimes use bar codes to sense orientations, and use solar cells or a single transformer to power the platform. Some small missiles have powered the platform with light from a window or optic fibers to the motor. A research topic is to suspend the platform with pressure from exhaust gases. Data is returned to the outside world via the transformers, or sometimes LEDs communicating with external photodiodes.

Strapdown systems

Lightweight digital computers permit the system to eliminate the gimbals, creating *strapdown* systems, so called because their sensors are simply strapped to the vehicle. This reduces the cost, eliminates gimbal lock, removes the need for some calibrations, and increases the reliability by eliminating some of the moving parts. Angular rate sensors called *rate gyros* measure how the angular velocity of the vehicle changes.

A strapdown system has a dynamic measurement range several hundred times that required by a gimbaled system. That is, it must integrate the vehicle's attitude changes in pitch, roll and yaw, as well as gross movements. Gimballed systems could usually do well with update rates of 50–60 Hz. However, strapdown systems normally update about 2000 Hz. The higher rate is needed to keep the maximum angular measurement within a practical range for real rate gyros: about 4 milliradians. Most rate gyros are now laser interferometers.

The data updating algorithms (*direction cosines* or quaternions) involved are too complex to be accurately performed except by digital electronics. However, digital computers are now so inexpensive and fast that rate gyro systems can now be practically used and mass-produced. The Apollo lunar module used a strapdown system in its backup Abort Guidance System (AGS).

Strapdown systems are nowadays commonly used in commercial and tactical applications (aircraft, missiles, etc.). However they are still not widespread in applications where superb accuracy is required (like submarine navigation or strategic ICBM guidance).

Motion-based alignment

The orientation of a gyroscope system can sometimes also be inferred simply from its position history (e.g., GPS). This is, in particular, the case with planes and cars, where the velocity vector usually implies the orientation of the vehicle body.

For example, Honeywell's *Align in Motion* is an initialization process where the initialization occurs while the aircraft is moving, in the air or on the ground. This is accomplished using GPS and an inertial reasonableness test, thereby allowing commercial data integrity requirements to be met. This process has been FAA certified to recover pure INS performance equivalent to stationary align procedures for civilian flight times up to 18 hours. It avoids the need for gyroscope batteries on aircraft.

Vibrating gyros

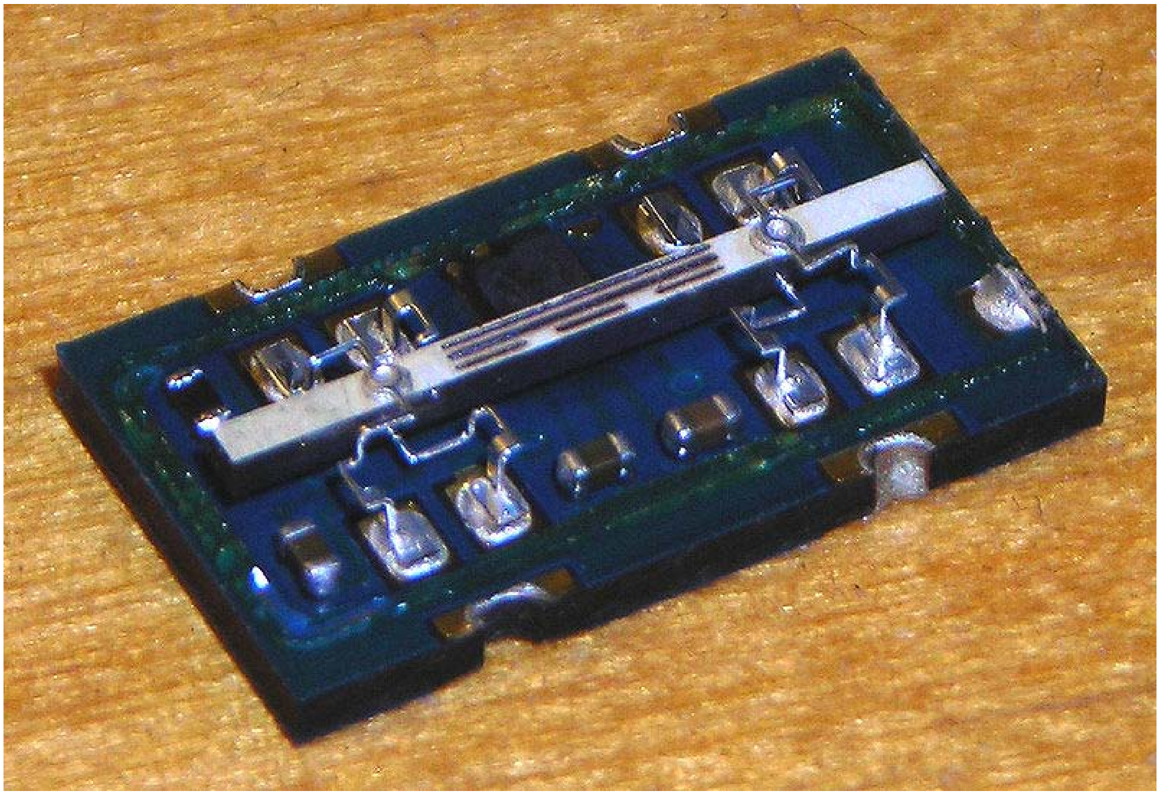
Less-expensive navigation systems, intended for use in automobiles, may use a vibrating structure gyroscope to detect changes in heading, and the odometer pickup to measure distance covered along the vehicle's track. This type of system is much less accurate than a higher-end INS, but it is adequate for the typical automobile application where GPS is the primary navigation system, and dead reckoning is only needed to fill gaps in GPS coverage when buildings or terrain block the satellite signals.

Hemispherical Resonator Gyros (wine glass or mushroom gyros)

If a standing wave is induced in a hemispheric resonant cavity, and then the resonant cavity is rotated, the spherical harmonic standing wave rotates through an angle different than the quartz resonator structure due to the Coriolis force. The movement of the outer case with respect to the standing wave pattern is proportional to the total rotation angle and can be sensed by appropriate electronics. The system resonators are machined from quartz due to its excellent mechanical properties. The electrodes that drive and sense the standing waves are deposited directly onto separate quartz structures that surround the resonator. These gyros can operate in either a whole angle mode (which gives them nearly unlimited rate capability) or a force rebalance mode that holds the standing wave in a fixed orientation with respect to the gyro housing (which gives them much better accuracy).

This system has almost no moving parts, and is very accurate. However it is still relatively expensive due to the cost of the precision ground and polished hollow quartz hemispheres. Northrop Grumman currently manufactures Inertial Measurement Units for spacecraft that use HRGs. These IMUs have demonstrated extremely high reliability since their initial use in 1996.

Quartz rate sensors



The quartz rate sensor inside an E-Sky model helicopter

This system is usually integrated on a silicon chip. It has two mass-balanced quartz tuning forks, arranged "handle-to-handle" so forces cancel. Aluminum electrodes evaporated onto the forks and the underlying chip both drive and sense the motion. The system is both manufacturable and inexpensive. Since quartz is dimensionally stable, the system can be accurate.

As the forks are twisted about the axis of the handle, the vibration of the tines tends to continue in the same plane of motion. This motion has to be resisted by electrostatic forces from the electrodes under the tines. By measuring the difference in capacitance between the two tines of a fork, the system can determine the rate of angular motion.

These products include 'tuning fork gyros'. Gyro is designed as an electronically-driven tuning fork, often fabricated out of a single piece of quartz or silicon. Such gyros operate in accordance with the dynamic theory that when an angle rate is applied to a translating body, a Coriolis force is generated.

Current state of the art non-military technology (as of 2005) can build small solid state sensors that can measure human body movements. These devices have no moving parts, and weigh about 50 grams.

Solid state devices using the same physical principles are used for image stabilization in small cameras or camcorders. These can be extremely small (≈5 mm) and are built with Microelectromechanical systems (MEMS) technologies.

MHD sensor

Sensors based on magnetohydrodynamic principles can be used to measure angular velocities.

Laser gyros

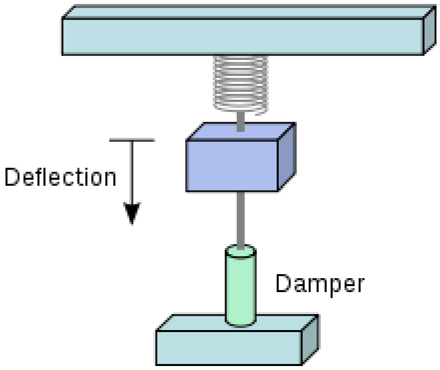
A ring laser gyro splits a beam of laser light into two beams in opposite directions through narrow tunnels in a closed optical circular path around the perimeter of a triangular block of temperature-stable Cervit glass with reflecting mirrors placed in each corner. When the gyro is rotating at some angular rate, the distance traveled by each beam becomes different—the shorter path being opposite to the rotation. The phase-shift between the two beams can be measured by an interferometer, and is proportional to the rate of rotation (Sagnac effect).

In practice, at low rotation rates the output frequency can drop to zero after the result of back scattering causing the beams to synchronise and lock together. This is known as a *lock-in*, or *laser-lock*. The result is that there is no change in the interference pattern, and therefore no measurement change.

To unlock the counter-rotating light beams, laser gyros either have independent light paths for the two directions (usually in fiber optic gyros), or the laser gyro is mounted on a piezo-electric dither motor that rapidly vibrates the laser ring back and forth about its input axis through the lock-in region to decouple the light waves.

The shaker is the most accurate, because both light beams use exactly the same path. Thus laser gyros retain moving parts, but they do not move as far.

Pendular accelerometers



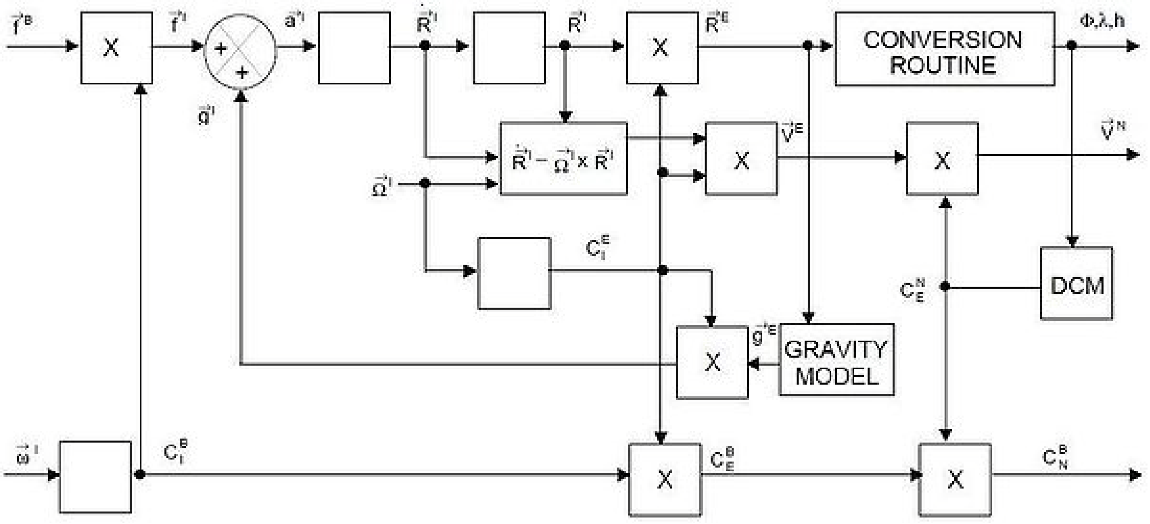
Principle of open loop accelerometer. Acceleration in the upward direction causes the mass to deflect downward.

The basic, open-loop accelerometer consists of a mass attached to a spring. The mass is constrained to move only in-line with the spring. Acceleration causes deflection of the mass and the offset distance is measured. The acceleration is derived from the values of deflection distance, mass, and the spring constant. The system must also be damped to avoid oscillation. A closed-loop accelerometer achieves higher performance by using a feedback loop to cancel the deflection, thus keeping the mass nearly stationary. Whenever the mass deflects, the feedback loop causes an electric coil to apply an equally negative force on the mass, cancelling the motion. Acceleration is derived from the amount of negative force applied. Because the mass barely moves, the non-linearities of the spring and damping system are greatly reduced. In addition, this accelerometer provides for increased bandwidth past the natural frequency of the sensing element.

Both types of accelerometers have been manufactured as integrated micromachinery on silicon chips.

Methodology

In one form, the navigational system of equations acquires linear and angular measurements from the inertial and body frame, respectively and calculates the final attitude and position in the NED frame of reference.



Where: f is specific force, ω is angular rate, a is acceleration, R is position, $\dot{R}$and V are velocity, Ω is the angular velocity of the earth, g is the acceleration due to gravity, Φ,λ and h are the NED location parameters. Also, super/subscripts of E, I and B are representing variables in the Earth centered, Inertial or Body reference frame, respectively and C is a transformation of reference frames.

Chapter 7

Glass Cockpit

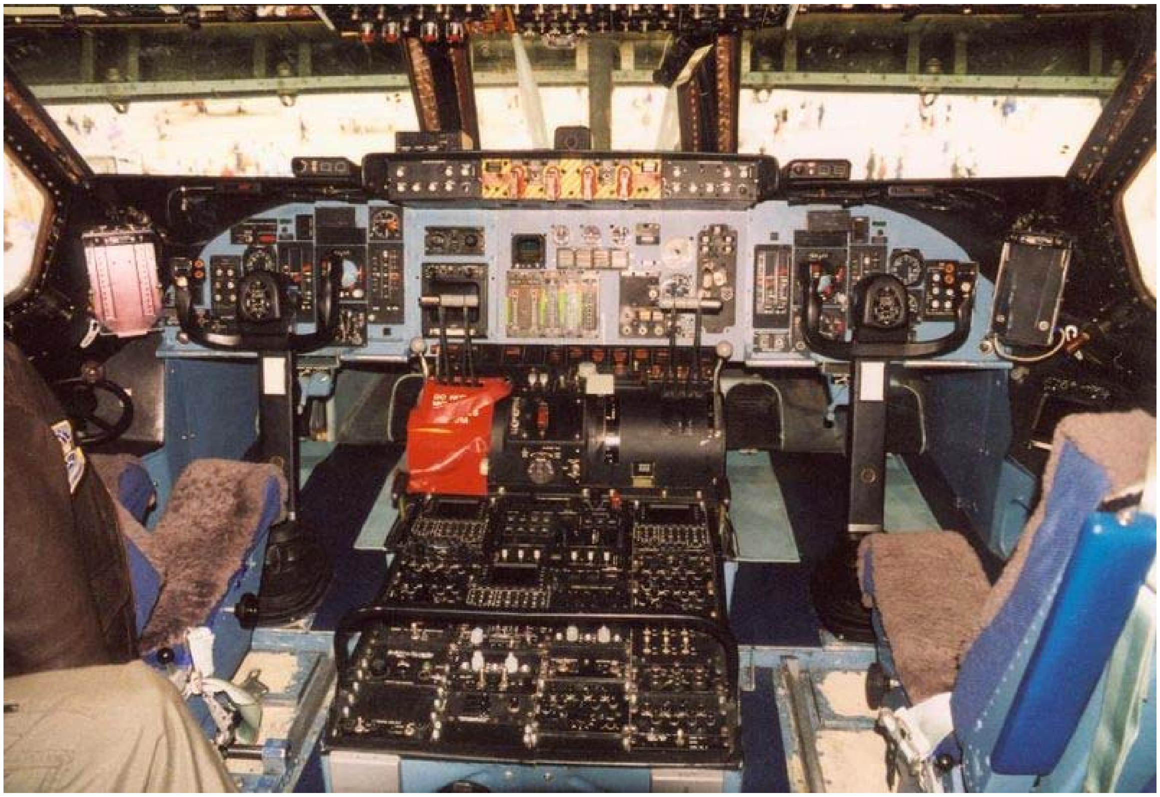
The Airbus A380 glass cockpit featuring "pull out keyboards and 2 wide computer screen on the sides for pilots".

A **glass cockpit** is an aircraft cockpit that features electronic instrument displays. Where a traditional cockpit relies on numerous mechanical gauges to display information, a glass cockpit uses several displays driven by flight management systems, that can be adjusted to display flight information as needed. This simplifies aircraft operation and navigation and allows pilots to focus only on the most pertinent information. They are also popular with airline companies as they usually eliminate the need for a flight engineer. In recent years the technology has become widely available in small aircraft.

As aircraft displays have modernized, the sensors that feed them have modernized as well. Traditional gyroscopic flight instruments have been replaced by electronic Attitude and Heading Reference Systems (AHRS) and Air Data Computers (ADCs), improving reliability and reducing cost and maintenance. GPS receivers are usually integrated into glass cockpits.

Early glass cockpits, found in the McDonnell Douglas MD-80/90, Boeing 737 Classic, 757 and 767-200/-300, and in the Airbus A300-600 and A310, used Electronic Flight Instrument Systems (EFIS) to display attitude and navigational information only, with traditional mechanical gauges retained for airspeed, altitude and vertical speed. Later glass cockpits, found in the Boeing 737NG, 747-400, 767-400, 777, A320 and later Airbuses, Ilyushin Il-96 and Tupolev Tu-204 have completely replaced the mechanical gauges and warning lights in previous generations of aircraft.

History



Instrument panel of a C-5A

New instrument panel for C-5 as part of AMP program

Prior to the 1970s, air transport operations were not considered sufficiently demanding to require advanced equipment like electronic flight displays. Also, computer technology was not at a level where sufficiently light and powerful circuits were available. The increasing complexity of transport aircraft, the advent of digital systems and the growing air traffic congestion around airports began to change that.

The average transport aircraft in the mid-1970s had more than one hundred cockpit instruments and controls, and the primary flight instruments were already crowded with indicators, crossbars, and symbols, and the growing number of cockpit elements were competing for cockpit space and pilot attention. As a result, NASA conducted research on displays that could process the raw aircraft system and flight data into an integrated, easily understood picture of the flight situation, culminating in a series of flights demonstrating a full glass cockpit system.

The success of the NASA-led glass cockpit work is reflected in the total acceptance of electronic flight displays beginning with the introduction of the MD-80 in 1979. Airlines and their passengers alike have benefited. The safety and efficiency of flights has been increased with improved pilot understanding of the aircraft's situation relative to its environment (or "situational awareness").

By the end of the 1990s, Liquid crystal display (LCD) panels were increasingly favored among aircraft manufacturers because of their efficiency, reliability and legibility. Earlier LCD panels suffered from poor legibility at some viewing angles and poor response times, making them unsuitable for aviation. Modern aircraft such as the Boeing 737 Next Generation, 777, 717, 747-400ER, 767-400ER, 747-8, and 787, Airbus A320 family (later versions), A330 (later versions), A340-500/600, A340-300 (later versions), A380 and A350 are fitted with glass cockpits consisting of LCD units.

The glass cockpit has become standard equipment in airliners, business jets, and military aircraft. It was even fitted into NASA's Space Shuttle orbiters *Atlantis*, *Columbia*, *Discovery*, and *Endeavour*, and the current Russian Soyuz TMA model spacecraft that was launched in 2002. By the end of the century glass cockpits began appearing in general aviation aircraft as well. By 2005, even basic trainers like the Piper Cherokee and Cessna 172 were shipping with glass cockpits as options (which nearly all customers chose), and many modern aircraft such as the Diamond Aircraft twin-engine travel and training aircraft DA42, and Cirrus Design SR20 and SR22 are available with glass cockpit only.

Usage

In commercial aviation

The Space Shuttle glass cockpit

Unlike the previous era of glass cockpits—where designers merely copied the look and feel of conventional electromechanical instruments onto cathode ray tubes—the new displays represent a true departure. They look and behave very similarly to other computers, with windows and data that can be manipulated with point-and-click devices. They also add terrain, approach charts, weather, vertical displays, and 3D navigation images.

The improved concepts enable aircraft makers to customize cockpits to a greater degree than previously. All of the manufacturers involved have chosen to do so in one way or another—such as using a trackball, thumb pad or joystick as a pilot-input device in a computer-style environment. Many of the modifications offered by the aircraft manufacturers improve situational awareness and customize the human-machine interface to increase safety.

Modern glass cockpits might include Synthetic Vision (SVS) or Enhanced Vision systems (EVS). Synthetic Vision systems display a realistic 3D depiction of the outside world (similar to a flight simulator), based on a database of terrain and geophysical features in conjunction with the attitude and position information gathered from the aircraft navigational systems. Enhanced Vision systems add real-time information from external sensors, such as an infrared camera.

All new airliners such as the Airbus A380, Boeing 787 and private jets such as Bombardier Global Express and Learjet use glass cockpits.

In general aviation

Garmin G1000 displays in a Cessna 182

Certain general aviation aircraft, such as the 4-seat Diamond Aircraft DA40, DA42 and DA50 and the 4-seat Cirrus Design SR20 and SR22, are available with glass cockpits. Systems such as the Garmin G1000 are now available on many new GA aircraft, including the classic Cessna 172. Some small aircraft can also be modified post-production to replace steam gauges.

Glass cockpits are also popular as a retrofit for older private jets and turboprops such as Dassault Falcons, Raytheon Hawkers, Bombardier Challenger, Cessna Citations, Gulfstreams, King Airs, Learjets, Astras and many others. Aviation service companies work closely with equipment manufacturers to address the needs of the owners of these aircraft.

Safety

As aircraft operation becomes more dependent on glass cockpit systems, flight crews must be trained to deal with possible failures. In one glass-cockpit aircraft, the Airbus A320, fifty incidents of glass-cockpit blackout have occurred. On 25 January 2008 United Airlines Flight 731 experienced a serious glass-cockpit blackout, losing half of the

ECAM displays as well as all radios, transponders, TCAS, and attitude indicators. Partially due to good weather and daylight conditions, the pilots were able to land successfully at Newark Airport without radio contact. Airbus has offered an optional fix, which the US NTSB has suggested to the US FAA as mandatory, but the FAA has yet to make it a requirement. A preliminary NTSB factsheet is available. In 2010, the NTSB published a study done on 8,000 general aviation light aircraft. The study found that, although aircraft equipped with glass cockpits had a lower overall accident rate, they also had a larger chance of being involved in a fatal accident. The NTSB Chairman said in response to the study,

"Training is clearly one of the key components to reducing the accident rate of light planes equipped with glass cockpits, and this study clearly demonstrates the life and death importance of appropriate training on these complex systems... While the technological innovations and flight management tools that glass cockpit equipped airplanes bring to the general aviation community should reduce the number of fatal accidents, we have not – unfortunately – seen that happen."

Chapter 8

Autopilot

Autopilot panel of an older Boeing 747 aircraft

An **autopilot** is a mechanical, electrical, or hydraulic system used to guide a vehicle without assistance from a human being. An autopilot can refer specifically to aircraft, self-steering gear for boats, or auto guidance of space craft and missiles. The autopilot of an aircraft is sometimes referred to as "George".

First autopilots

In the early days of aviation, aircraft required the continuous attention of a pilot in order to fly safely. As aircraft range increased allowing flights of many hours, the constant attention led to serious fatigue. An autopilot is designed to perform some of the tasks of the pilot.

The first aircraft autopilot was developed by Sperry Corporation in 1912. The autopilot connected a gyroscopic Heading indicator and attitude indicator to hydraulically operated elevators and rudder (ailerons were not connected as wing dihedral was counted upon to produce the necessary roll stability.) It permitted the aircraft to fly straight and level on a compass course without a pilot's attention, greatly reducing the pilot's workload.

Lawrence Sperry (the son of famous inventor Elmer Sperry) demonstrated it two years later in 1914 at an aviation safety contest held in Paris. At the contest, Lawrence Sperry demonstrated the credibility of the invention were shown by flying the aircraft with his hands away from the controls and visible to onlookers of the contest. This autopilot system was also capable of performing take-off and landing, and the French military command showed immediate interest in the autopilot system. Wiley Post used a Sperry autopilot system to fly alone around the world in less than eight days in 1933.

Further development of the autopilot were performed, such as improved control algorithms and hydraulic servomechanisms. Also, inclusion of additional instrumentation such as the radio-navigation aids made it possible to fly during night and in bad weather. In 1947 a US Air Force C-53 made a transatlantic flight, including takeoff and landing, completely under the control of an autopilot.

In the early 1920s, the Standard Oil tanker *J.A Moffet* became the first ship to use an autopilot.

Modern autopilots

Not all of the passenger aircraft flying today have an autopilot system. Older and smaller general aviation aircraft especially are still hand-flown, while small airliners with fewer than twenty seats may also be without an autopilot as they are used on short-duration flights with two pilots. The installation of autopilots in aircraft with more than twenty seats is generally made mandatory by international aviation regulations. There are three levels of control in autopilots for smaller aircraft. A single-axis autopilot controls an aircraft in the roll axis only; such autopilots are also known colloquially as "wing levellers", reflecting their limitations. A two-axis autopilot controls an aircraft in the pitch axis as well as roll, and may be little more than a "wing leveller" with limited pitch-oscillation-correcting ability; or it may receive inputs from on-board radio navigation systems to provide true automatic flight guidance once the aircraft has taken off until shortly before landing; or its capabilities may lie somewhere between these two extremes. A three-axis autopilot adds control in the yaw axis and is not required in many small aircraft.

Autopilots in modern complex aircraft are three-axis and generally divide a flight into taxi, takeoff, ascent, level, descent, approach and landing phases. Autopilots exist that automate all of these flight phases except the taxiing. An autopilot-controlled landing on a runway and controlling the aircraft on rollout (i.e. keeping it on the centre of the runway) is known as a CAT IIIb landing or Autoland, available on many major airports' runways today, especially at airports subject to adverse weather phenomena such as fog. Landing, rollout and taxi control to the aircraft parking position is known as CAT IIIc. This is not used to date but may be used in the future. An autopilot is often an integral component of a Flight Management System.

Modern autopilots use computer software to control the aircraft. The software reads the aircraft's current position, and controls a Flight Control System to guide the aircraft. In such a system, besides classic flight controls, many autopilots incorporate thrust control capabilities that can control throttles to optimize the air-speed, and move fuel to different tanks to balance the aircraft in an optimal attitude in the air. Although autopilots handle new or dangerous situations inflexibly, they generally fly an aircraft with a lower fuel-consumption than a human pilot.

The autopilot in a modern large aircraft typically reads its position and the aircraft's attitude from an inertial guidance system. Inertial guidance systems accumulate errors over time. They will incorporate error reduction systems such as the carousel system that rotates once a minute so that any errors are dissipated in different directions and have an overall nulling effect. Error in gyroscopes is known as drift. This is due to physical properties within the system, be it mechanical or laser guided, that corrupt positional data. The disagreements between the two are resolved with digital signal processing, most often a six-dimensional Kalman filter. The six dimensions are usually roll, pitch, yaw, altitude, latitude and longitude. Aircraft may fly routes that have a required performance factor, therefore the amount of error or actual performance factor must be monitored in order to fly those particular routes. The longer the flight the more error accumulates within the system. Radio aids such as DME, DME updates and GPS may be used to correct the aircraft position.

Computer system details

The hardware of an autopilot varies from implementation to implementation, but is generally designed with redundancy and reliability as foremost considerations. For example, the Rockwell Collins AFDS-770 Autopilot Flight Director System used on the Boeing 777, uses triplicated FCP-2002 microprocessors which have been formally verified and are fabricated in a radiation resistant process.

Software and hardware in an autopilot is tightly controlled, and extensive test procedures are put in place.

Some autopilots also use design diversity. In this safety feature, critical software processes will not only run on separate computers and possibly even using different architectures, but each computer will run software created by different engineering teams, often being programmed in different programming languages. It is generally considered unlikely that different engineering teams will make the same mistakes. As the software becomes more expensive and complex, design diversity is becoming less common because fewer engineering companies can afford it. The flight control computers on the Space Shuttle uses this design: there are five computers, four of which redundantly run identical software, and a fifth backup running software that was developed independently. The software on the fifth system provides only the basic functions needed to fly the Shuttle, further reducing any possible commonality with the software running on the four primary systems.

Categories

Instrument-aided landings are defined in categories by the International Civil Aviation Organization. These are dependent upon the required visibility level and the degree to which the landing can be conducted automatically without input by the pilot.

CAT I - This category permits pilots to land with a decision height of 200 ft (61 m) and a forward visibility or Runway Visual Range (RVR) of 550 m. Simplex autopilots are sufficient.

CAT II - This category permits pilots to land with a decision height between 200 ft and 100 ft (≈ 30 m) and a RVR of 300 m. Autopilots have a fail passive requirement.

CAT IIIa -This category permits pilots to land with a decision height as low as 50 ft (15 m) and a RVR of 200 m. It needs a fail-passive autopilot. There must be only a 10^{-6} probability of landing outside the prescribed area.

CAT IIIb - As IIIa but with the addition of automatic roll out after touchdown incorporated with the pilot taking control some distance along the runway. This category permits pilots to land with a decision height less than 50 feet or no decision height and a forward visibility of 250 ft (76 m, compare this to aircraft size, some of which are now over 70 m long) or 300 ft (91 m) in the United States. For a landing-without-decision aid, a fail-operational autopilot is needed. For this category some form of runway guidance system is needed: at least fail-passive but it needs to be fail-operational for landing without decision height or for RVR below 100 m.

CAT IIIc - As IIIb but without decision height or visibility minimums, also known as "zero-zero".

Fail-passive autopilot: in case of failure, the aircraft stays in a controllable position and the pilot can take control of it to go around or finish landing. It is usually a dual-channel system.

Fail-operational autopilot: in case of a failure below alert height, the approach, flare and landing can still be completed automatically. It is usually a triple-channel system or dual-dual system.

Radio-controlled models

In radio-controlled modelling, and especially RC aircraft and helicopters, an autopilot is usually a set of extra hardware and software that deals with pre-programming the model's flight.

Chapter 9

Electronic Flight Instrument System

EFIS on an Airbus A380

EFIS on an Eclipse 500

Garmin G1000 on a Diamond DA42

An **Electronic Flight Instrument System** (EFIS) is a flight deck instrument display system in which the display technology used is electronic rather than electromechanical. EFIS normally consists of a primary flight display (PFD), multi-function display (MFD) and Engine Indicating and Crew Alerting System (EICAS) display. Although cathode ray tube (CRT) displays were used at first, liquid crystal displays (LCD) are now more common.

The complex electromechanical attitude director indicator (ADI) and horizontal situation indicator (HSI) were the first candidates for replacement by EFIS. However, there are now few flight deck instruments for which no electronic display is available.

Overview

EFIS installations vary greatly. A light aircraft might be equipped with one display unit, on which are displayed flight and navigation data. A wide-body aircraft is likely to have six or more display units.

Typical EFIS displays and controls can be seen at this B737 technical information web site. The equivalent electromechanical instruments are also shown here.

An EFIS installation will have the following components:

- Displays
- Controls
- Data processors

A basic EFIS might have all these facilities in the one unit.

Display units

Primary Flight Display (PFD)

On the flight deck, the display units are the most obvious parts of an EFIS system, and are the features which give rise to the name "glass cockpit". The display unit taking the place of the ADI is called the primary flight display (PFD). If a separate display replaces the HSI, it is called the navigation display. The PFD displays all information critical to flight, including calibrated airspeed, altitude, heading, attitude, vertical speed and yaw. The PFD is designed to improve a pilot's situational awareness by integrating this information into a single display instead of six different analog instruments, reducing the amount of time necessary to monitor the instruments. PFDs also increase situational awareness by alerting the aircrew to unusual or potentially hazardous conditions — for example, low airspeed, high rate of descent — by changing the color or shape of the display or by providing audio alerts.

The names Electronic Attitude Director Indicator and Electronic Horizontal Situation Indicator are used by some manufacturers. However, a simulated ADI is only the centerpiece of the PFD. Additional information is both superimposed on and arranged around this graphic.

Multi-function displays can render a separate navigation display unnecessary. Another option is to use one large screen to show both the PFD and navigation display.

The PFD and navigation display (and multi-function display, where fitted) are often physically identical. The information displayed is determined by the system interfaces where the display units are fitted. Thus, spares holding is simplified: the one display unit can be fitted in any position.

LCD units generate less heat than CRTs; an advantage in a congested instrument panel. They are also lighter, and occupy a lower volume.

Multi-Function Display (MFD) / Navigation Display (ND)

The MFD (Multi-Function Display) displays navigational and weather information from multiple systems. MFDs are most frequently designed as "chart-centric", where the aircrew can overlay different information over a map or chart. Examples of MFD overlay information include the aircraft's current route plan, weather information from either on-board radar or lightning detection sensors or ground-based sensors, e.g., NEXRAD, restricted airspace and aircraft traffic. The MFD can also be used to view other non-overlay type of data (e.g., current route plan) and calculated overlay-type data, e.g., the glide radius of the aircraft, given current location over terrain, winds, and aircraft speed and altitude.

MFDs can also display information about aircraft systems, such as fuel and electrical systems. As with the PFD, the MFD can change the color or shape of the data to alert the aircrew to hazardous situations.

Engine Indications and Crew Alerting System (EICAS) / Electronic Centralized Aircraft Monitoring (ECAM)

EICAS (Engine Indications and Crew Alerting System) displays information about the aircraft's systems, including its fuel, electrical and propulsion systems (engines). EICAS displays are often designed to mimic traditional round gauges while also supplying digital readouts of the parameters.

EICAS improves situational awareness by allowing the aircrew to view complex information in a graphical format and also by alerting the crew to unusual or hazardous situations. For example, if an engine begins to lose oil pressure, the EICAS might sound an alert, switch the display to the page with the oil system information and outline the low oil pressure data with a red box. Unlike traditional round gauges, many levels of warnings and alarms can be set. Proper care must be taken when designing EICAS to ensure that the aircrew are always provided with the most important information and not overloaded with warnings or alarms.

ECAM is a similar system used by Airbus, which in addition to providing EICAS functions also recommend remedial action.

Control panels

The pilots are provided with controls, with which they select display range and mode (for example, map or compass rose) and enter data (such as selected heading).

Where inputs by the pilot are used by other equipment, data buses broadcast the pilot's selections so that the pilot only needs to enter the selection once. For example, the pilot selects the desired level-off altitude on a control unit. The EFIS repeats this selected altitude on the PFD and by comparing it with the actual altitude (from the air data computer) generates an altitude error display. This same altitude selection is used by the automatic flight control system to level off, and by the altitude alerting system to provide appropriate warnings.

Data processors

The EFIS visual display is produced by the symbol generator. This receives data inputs from the pilot, signals from sensors, and EFIS format selections made by the pilot. The symbol generator can go by other names, such as display processing computer, display electronics unit, etc.

The symbol generator does more than generate symbols. It has (at the least) monitoring facilities, a graphics generator and a display driver. Inputs from sensors and controls arrive via data buses, and are checked for validity. The required computations are performed, and the graphics generator and display driver produce the inputs to the display units.

Monitoring

Like personal computers, flight instrument systems need power-on-self-test facilities and continuous self-monitoring. Flight instrument systems, however, need additional monitoring capabilities:

- Input validation — verify that each sensor is providing valid data
- Data comparison — cross check inputs from duplicated sensors
- Display monitoring — detect failures within the instrument system

Former practice

Traditional (electromechanical) displays were equipped with synchro mechanisms which would transmit, to an instrument comparator, the pitch, roll and heading that were actually being shown on the Captain's and First Officer's instruments. The comparator warned of excessive differences between the Captain and First Officer displays. Even a fault as far *downstream* as a jam in, say, the roll mechanism of an ADI would trigger a comparator warning.

The instrument comparator thus provided both comparator monitoring and display monitoring.

Comparator monitoring

With EFIS, the comparator function is as simple as ever. Is the roll data (bank angle) from sensor 1 the same as the roll data from sensor 2? If not, put a warning caption (such as **CHECK ROLL**) on both PFDs. Comparison monitors will give warnings for airspeeds, pitch, roll and altitude indications. The more advanced EFIS systems, more comparator monitors will be enabled.

Display monitoring

An EFIS display allows no easy re-transmission of what is shown on the display. What is required is a new approach to display monitoring that provides safety equivalent to that of the traditional system. One solution is to keep the display unit as simple as possible, so that it is unable to introduce errors. The display unit either works or does not work. A failure is always obvious, never insidious. Now the monitoring function can be shifted *upstream* to the output of the symbol generator.

In this technique, each symbol generator contains two display monitoring channels. One channel, the internal, samples the output from its own symbol generator to the display unit and computes, for example, what roll attitude should produce that indication. This computed roll attitude is then compared with the roll attitude input to the symbol generator from the INS or AHRS. Any difference has probably been introduced by faulty processing, and triggers a warning on the relevant display.

The external monitoring channel carries out the same check on the symbol generator on the other side of the flight deck: the Captain's symbol generator checks the First Officer's, the First Officer's checks the Captain's. Whichever symbol generator detects a fault, puts up a warning on its own display.

The external monitoring channel also checks sensor inputs (to the symbol generator) for reasonableness. A spurious input, such as a radio height greater than the radio altimeter's maximum, results in a warning.

Human factors

Clutter

At various stages of a flight, a pilot uses different combinations of data. Ideally, only the data in use would be displayed, but an electromechanical instrument has to be in view all the time. To improve display clarity, intricate mechanisms are used on ADIs and HSIs to remove superfluous indications temporarily, e.g., removing the glide slope scale when it is not being used.

With EFIS, some indications, e.g., engine vibration, might not be displayed under normal conditions. If limits are exceeded, then the reading will be displayed. In similar fashion, EFIS is programmed to show the glideslope scale and pointer only during an ILS approach.

If a failure of input data is detected, electromechanical instruments add yet another indicator to the display. Typically, a bar is dropped across the erroneous data. EFIS, on the other hand, removes invalid data from the display and substitutes an appropriate warning.

A de-clutter mode is activated automatically when the pilot's attention is required to be focused on a specific item. For example, if the aircraft is pitched up or down above a specified pitch, usually 30 to 60 degrees, the attitude indicator will de-clutter items from sight until the pitch is brought to an acceptable level. This allows the pilot to focus on the most important matter of aircraft control.

Color

Although color has long been used in traditional instruments, it is restricted to aiding in identification of the data. There is no means of changing the color of any display component.

This restriction has been lifted with EFIS. For example, as an aircraft approaches the glideslope, a blue caption could indicate glide slope is armed; on capture the color might change to green.

On a typical EFIS system, the navigation needles are color coded to reflect the type of navigation being used. Green needles are used for ground based navigation such as VORs, Localizers and ILS systems. Magenta needles are used for GPS navigation.

Advantages

EFIS offers **versatility** by avoiding some of the physical limitations of traditional instruments. Thus, the same display which shows a course deviation indicator, can be switched to show the planned track provided by an area navigation or flight management system. If desired, the weather radar picture can then be superimposed on the displayed route.

The **flexibility** afforded by software modifications, minimises costs when new aircraft equipment and new regulations are introduced. The EFIS system can be updated with new software to extend its capabilities. Such updates introduced in the 1990s included enhanced GPWS, and TCAS.

A degree of **redundancy** is available even with the simple two-screen EFIS installation. Should the PFD fail, transfer switching repositions its vital information to the screen normally occupied by the navigation display.

Advances in EFIS

In the late 1980s, EFIS became standard equipment on most Boeing and Airbus airliners, and many business aircraft adopted EFIS in the 1990s.

Recent advances in computing power and reductions in the cost of liquid-crystal displays and navigational sensors (such as GPS and Attitude and Heading Reference Systems) have finally brought EFIS to general aviation aircraft. Notable examples are the Garmin G1000 and Chelton Flight Systems EFIS-SV.

Several EFIS manufacturers have focused on the experimental aircraft market, producing EFIS and EICAS systems for as little as US$1,000. The low cost is possible for several reasons, including steep drops in sensor prices and a lack of requirements to receive Federal Aviation Administration certification. This latter point restricts their use to experimental aircraft and certain other aircraft categories depending on local regulations. Uncertified EFIS systems are also found in Sport Pilot category aircraft, including factory built, microlight and ultralight aircraft. These systems can be fitted to certified aircraft in some cases as secondary or backup systems depending on local aviation authorities rules and regulations.

Chapter 10

Pitot-Static System

A **pitot-static system** is a system of pressure-sensitive instruments that is most often used in aviation to determine an aircraft's airspeed, Mach number, altitude, and altitude trend. A pitot-static system generally consists of a pitot tube, a static port, and the pitot-static instruments. This equipment is used to measure the forces acting on a vehicle as a function of the temperature, density, pressure and viscosity of the fluid in which it is operating. Other instruments that might be connected are air data computers, flight data recorders, altitude encoders, cabin pressurization controllers, and various airspeed switches. Errors in pitot-static system readings can be extremely dangerous as the information obtained from the pitot static system, such as altitude, is often critical to a successful flight. Several commercial airline disasters have been traced to a failure of the pitot-static system.

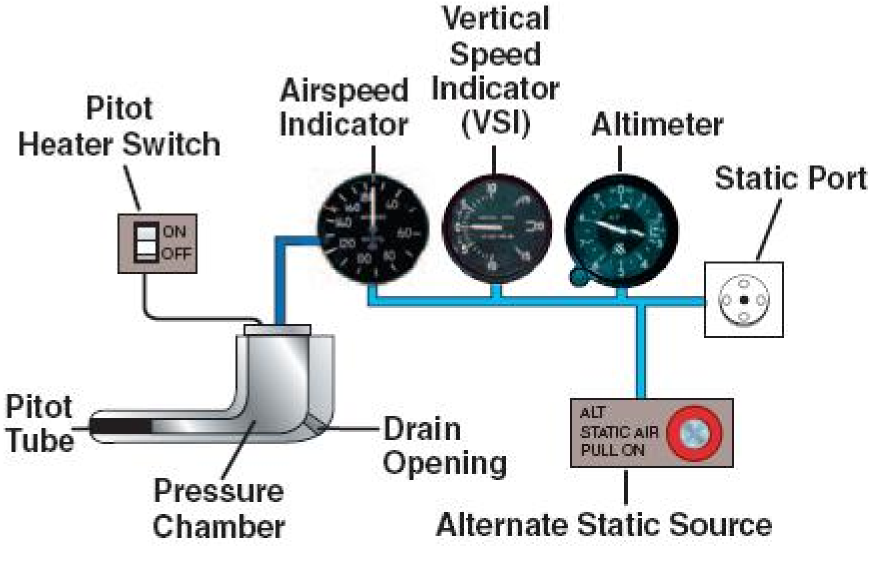
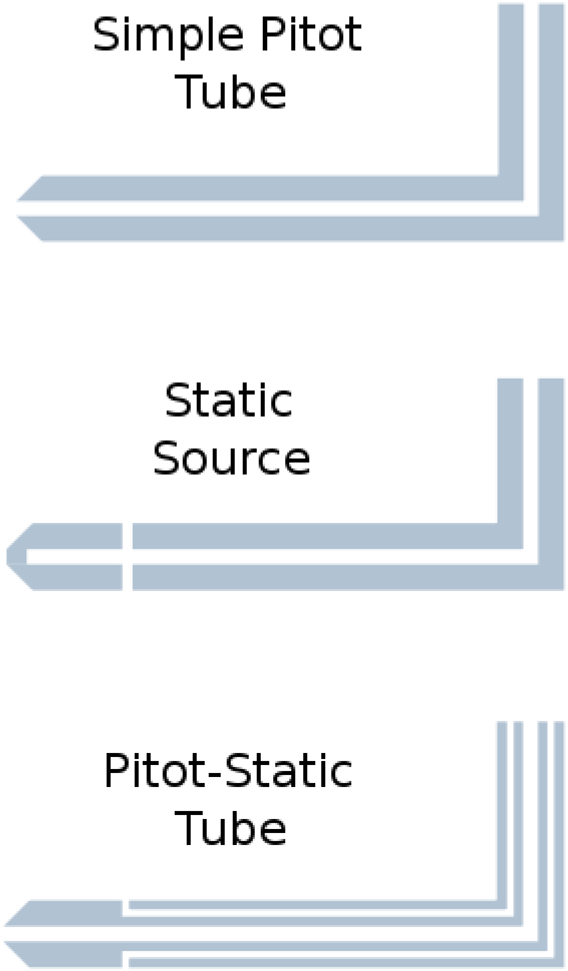


Diagram of a pitot-static system including the pitot tube, pitot-static instruments and static port

Pitot-static pressure



Examples of pitot tube, static tube, and pitot-static tube.

The pitot-static system of instruments uses the principle of air pressure gradient. It works by measuring pressures or pressure differences and using these values to assess the speed and altitude. These pressures can be measured either from the static port (static pressure) or the pitot tube (pitot pressure). The static pressure is used in all measurements, while the pitot pressure is only used to determine airspeed.

Pitot pressure

The pitot pressure is obtained from the pitot tube. The pitot pressure is a measure of ram air pressure (the air pressure created by vehicle motion or the air ramming into the tube), which, under ideal conditions, is equal to stagnation pressure, also called total pressure. The pitot tube is most often located on the wing or front section of an aircraft, facing forward, where its opening is exposed to the relative wind. By situating the pitot tube in such a location, the ram air pressure is more accurately measured since it will be less distorted by the aircraft's structure. When airspeed increases, the ram air pressure is increased, which can be translated by the airspeed indicator.

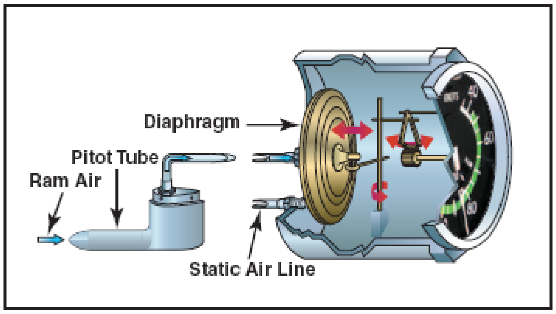
Static pressure

The static pressure is obtained through a static port. The static port is most often a flush-mounted hole on the fuselage of an aircraft, and is located where it can access the air flow in a relatively undisturbed area. Some aircraft may have a single static port, while others may have more than one. In situations where an aircraft has more than one static port, there is usually one located on each side of the fuselage. With this positioning, an average pressure can be taken, which allows for more accurate readings in specific flight situations. An alternative static port may be located inside the cabin of the aircraft as a backup for when the external static port(s) are blocked. A pitot-static tube effectively integrates the static ports into the pitot probe. It incorporates a second coaxial tube (or tubes) with pressure sampling holes on the sides of the probe, outside the direct airflow, to measure the static pressure.When aircraft climb, static pressure will decreases.

Multiple pressure

Some pitot-static systems incorporate single probes that contain multiple pressure-transmitting ports that allow for the sensing of air pressure, angle of attack, and angle of sideslip data. Depending on the design, such air data probes may be referred to as 5-hole or 7-hole air data probes. Differential pressure sensing techniques can be used to produce angle of attack and angle of sideslip indications.

Pitot-static instruments



Airspeed indicator diagram showing pressure sources from both the pitot tube and static port

The pitot-static system obtains pressures for interpretation by the pitot-static instruments. While the explanations below explain traditional, mechanical instruments, many modern aircraft use an air data computer (ADC) to calculate airspeed, rate of climb, altitude and Mach number. In some aircraft, two ADCs receive total and static pressure from independent pitot tubes and static ports, and the aircraft's flight data computer compares the information from both computers and checks one against the other. There are also "standby instruments", which are back-up pneumatic instruments employed in the case of problems with the primary instruments.

Airspeed indicator

The airspeed indicator is connected to both the pitot and static pressure sources. The difference between the pitot pressure and the static pressure is called "impact pressure". The greater the impact pressure, the higher the airspeed reported. A traditional mechanical airspeed indicator contains a pressure diaphragm that is connected to the pitot tube. The case around the diaphragm is airtight and is vented to the static port. The higher the speed, the higher the ram pressure, the more pressure exerted on the diaphragm, and the larger the needle movement through the mechanical linkage.

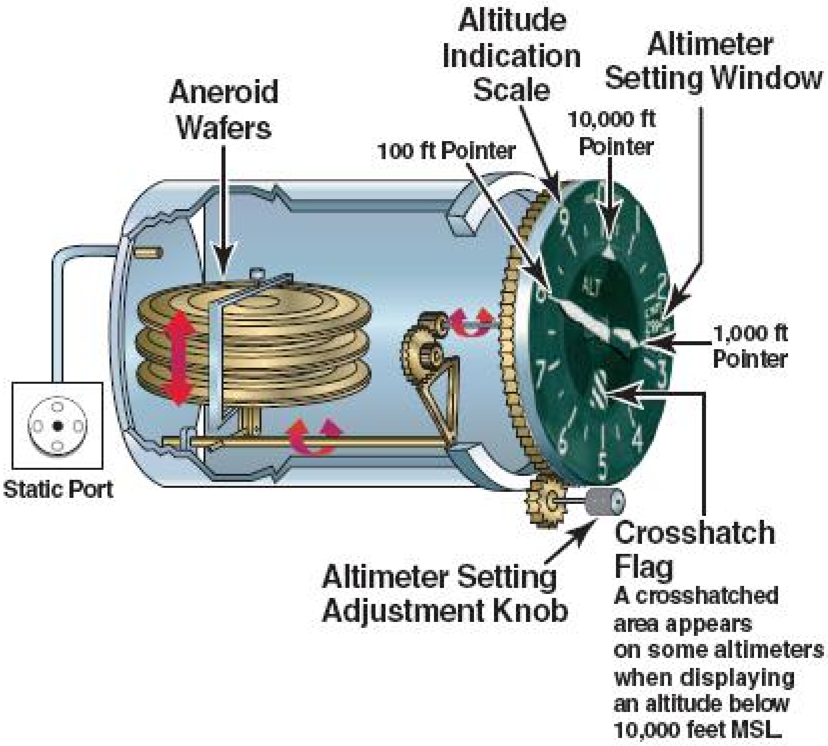


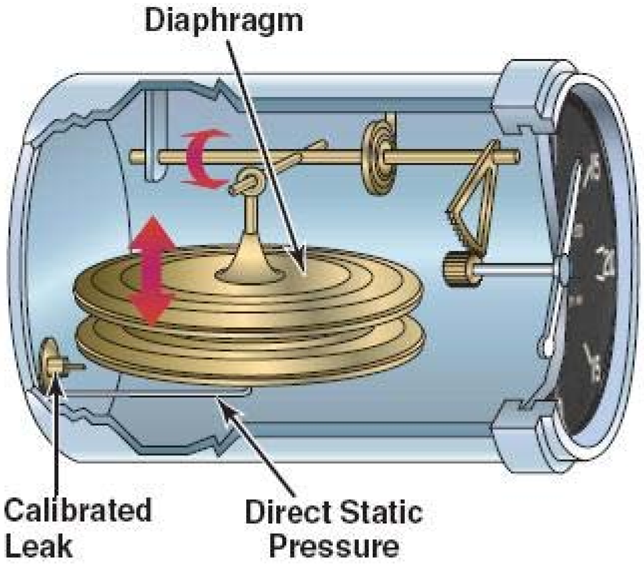
Diagram of an altimeter

Altimeter

The pressure altimeter, also known as the barometric altimeter, is used to determine changes in air pressure that occur as the aircraft's altitude changes. Pressure altimeters must be calibrated prior to flight to register the pressure as an altitude above sea level. The instrument case of the altimeter is airtight and has a vent to the static port. Inside the instrument, there is a sealed aneroid barometer. As pressure in the case decreases, the internal barometer expands, which is mechanically translated into a determination of altitude. The reverse is true when descending from higher to lower altitudes.

Machmeter

Aircraft designed to operate at transonic or supersonic speeds will incorporate a machmeter. The machmeter is used to show the ratio of true airspeed in relation to the speed of sound. Most supersonic aircraft are limited as to the maximum Mach number they can fly, which is known as the "Mach limit". The Mach number is displayed on a machmeter as a decimal fraction.



A vertical airspeed indicator

Vertical airspeed indicator

The variometer, also known as the vertical speed indicator (VSI) or the vertical velocity indicator (VVI), is the pitot-static instrument used to determine whether or not an aircraft is flying in level flight. The vertical airspeed specifically shows the rate of climb or the rate of descent, which is measured in feet per minute or meters per second. The vertical airspeed is measured through a mechanical linkage to a diaphragm located within the instrument. The area surrounding the diaphragm is vented to the static port through a calibrated leak (which also may be known as a "restricted diffuser"). When the aircraft begins to increase altitude, the diaphragm will begin to contract at a rate faster than that of the calibrated leak, causing the needle to show a positive vertical speed. The reverse of this situation is true when an aircraft is descending. The calibrated leak varies from model to model, but the average time for the diaphragm to equalize pressure is between 6 and 9 seconds.

Pitot-static errors

There are several situations that can affect the accuracy of the pitot-static instruments. Some of these involve failures of the pitot-static system itself—which may be classified as "system malfunctions"—while others are the result of faulty instrument placement or other environmental factors—which may be classified as "inherent errors".

System malfunctions

Blocked pitot tube

A blocked pitot tube is a pitot-static problem that will only affect airspeed indicators. A blocked pitot tube will cause the airspeed indicator to register an increase in airspeed when the aircraft climbs, even though actual airspeed is constant. This is caused by the pressure in the pitot system remaining constant when the atmospheric pressure (and static pressure) are decreasing. In reverse, the airspeed indicator will show a decrease in airspeed when the aircraft descends. The pitot tube is susceptible to becoming clogged by ice, water, insects or some other obstruction. For this reason, aviation regulatory agencies such as the U.S. Federal Aviation Administration (FAA) recommend that the pitot tube be checked for obstructions prior to any flight. To prevent icing, many pitot tubes are equipped with a heating element. A heated pitot tube is required in all aircraft certificated for instrument flight except aircraft certificated as Experimental Amateur-Built.

Blocked static port

A blocked static port is a more serious situation because it affects all pitot-static instruments. One of the most common causes of a blocked static port is airframe icing. A blocked static port will cause the altimeter to freeze at a constant value, the altitude at which the static port became blocked. The vertical speed indicator will become frozen at zero and will not change at all, even if vertical airspeed increases or decreases. The airspeed indicator will reverse the error that occurs with a clogged pitot tube and cause the airspeed be read less than it actually is as the aircraft climbs. When the aircraft is descending, the airspeed will be over-reported. In most aircraft with unpressurized cabins, an alternative static source is available and can be toggled from within the cockpit of the airplane.

Inherent errors

Inherent errors may fall into several categories, each affecting different instruments. *Density errors* affect instruments reporting airspeed and altitude. This type of error is caused by variations of pressure and temperature in the atmosphere. A *compressibility error* can arise because the impact pressure will cause the air to compress in the pitot tube. At standard sea level pressure altitude the calibration equation correctly accounts for the compression so there is no compressibility error at sea level. At higher altitudes the compression is not correctly accounted for and will cause the instrument to read greater than equivalent airspeed. A correction may be obtained from a chart. Compressibility error becomes significant at altitudes above 10,000 feet (3,000 m) and at airspeeds greater than 200 knots (370 km/h). *Hysteresis* is an error that is caused by mechanical properties of the aneroid capsules located within the instruments. These capsules, used to determine pressure differences, have physical properties that resist change by retaining a given shape, even though the external forces may have changed. *Reversal errors* are caused by a false static pressure reading. This false reading may be caused by abnormally large changes in an aircraft's pitch. A large change in pitch will cause a momentary showing of movement in the opposite direction. Reversal errors primarily affect altimeters and vertical speed indicators.

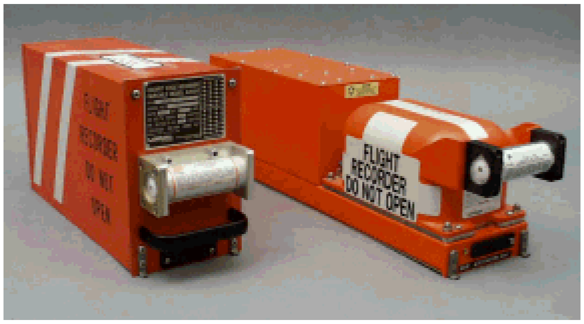
Position errors

Another class of inherent errors is that of position error. A position error is produced by the aircraft's static pressure being different from the air pressure remote from the aircraft. This error is caused by the air flowing past the static port at a speed different from the aircraft's true airspeed. Position errors may provide positive or negative errors, depending on one of several factors. These factors include airspeed, angle of attack, aircraft weight, acceleration, aircraft configuration, and in the case of helicopters, rotor downwash. There are two categories of position errors, which are "fixed errors" and "variable errors". Fixed errors are defined as errors which are specific to a particular make of aircraft. Variable errors are caused by external factors such as deformed panels obstructing the flow of air, or particular situations which may overstress the aircraft.

Chapter 11

Flight Data Recorder

An example of an FDR (flight data recorder). (English translation: FLIGHT RECORDER DO NOT OPEN)



Flight data recorder and cockpit voice recorder

A **flight data recorder** (**FDR**) (also **ADR**, for **accident data recorder**) is an electronic device employed to record any instructions sent to any between electronic systems on an aircraft. It is a device used to record specific aircraft performance parameters. Another kind of flight recorder is the cockpit voice recorder (CVR), which records conversation in the cockpit, radio communications between the cockpit crew and others (including conversation with air traffic control personnel), as well as ambient sounds. In some cases, both functions have been combined into a single unit. The current applicable FAA TSO is C124b titled Flight Data Recorder Systems.

Popularly referred to as a "black box", the data recorded by the FDR is used for accident investigation, as well as for analyzing air safety issues, material degradation and engine performance. Due to their importance in investigating accidents, these ICAO-regulated devices are carefully engineered and stoutly constructed to withstand the force of a high speed impact and the heat of an intense fire. Contrary to the "black box" reference, the exterior of the FDR is coated with heat-resistant bright Red paint for high visibility in wreckage, and the unit is usually mounted in the aircraft's empennage (tail section), where it is more likely to survive a severe crash. Following an accident, the recovery of the FDR is usually a high priority for the investigating body, as analysis of the recorded parameters can often detect and identify causes or contributing factors.

History

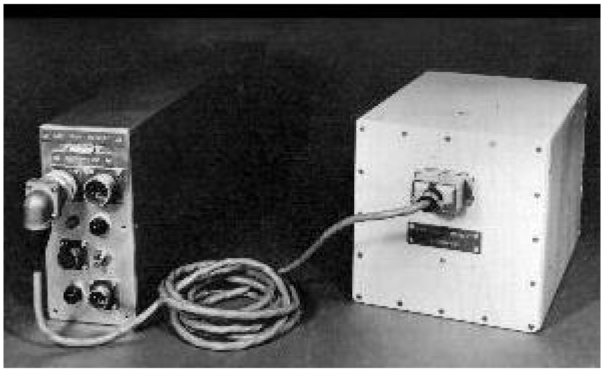
As with many successful devices, probably no single person could be credited with the invention of the flight data recorder. However, one of the earliest and proven attempts was made by François Hussenot and Paul Beaudouin in 1939 at the Marignane flight test center, France, with their "type HB" flight recorder. This was an essentially photograph-based device, because the record was made on a scrolling eight meters long by 88 milimeters wide photographic film. The latent image was made by a thin ray of light deviated by a mirror tilted according to the magnitude of the data to record (altitude, speed, etc). A pre-production run of 25 "HB" recorders was ordered in 1941 and HB recorders remained in use in French test centers well into the seventies In 1947, Hussenot, Beaudouin and associate Marcel Ramolfo founded the Société Française d'Instruments de Mesure to market their design. This company went on becoming a major supplier of data recorders, used not only aboard aircraft but also trains and other vehicles. SFIM is today part of the Safran group and is still present on the flight recorder market.

The advantage of the film technology was that it could be easily developed afterwards and provides a durable, visual feedback of the flight parameters without needing any playback device. On the other hand, unlike magnetic bands or later flash memory-based technology, a photographic film cannot be erased and recycled, and so it must be changed periodically. As such, this technology was reserved for one-shot uses, mostly during planned test flights; and it was not mounted aboard civilian aircraft during routine commercial flights. Also, the cockpit conversation was not recorded.

Another form of flight data recorder was developed in the UK during World War II. Len Harrison and Vic Husband developed a unit that could withstand a crash and fire to keep the flight data intact. This unit used copper foil as the recording medium with various styli indicating various instruments / aircraft controls which indented the copper foil. The copper foil was periodically advanced at set periods of time therefore giving a history of the instruments /control settings of the aircraft. This unit was developed at Farnborough for the Ministry of Aircraft Production. At the wars end the Ministry got Harrison and Husband to sign over their invention to them and the Ministry patented it under British patent 19330/45. This unit was the forerunner of today's black boxes being able to withstand conditions that aircrew could not.

The first prototype coupled FDR/CVR designed with civilian aircraft in mind, for explicit post-crash examination purposes, was produced in 1956 by Dr. David Warren of the Defence Science and Technology Organisations', Aeronautical Research Laboratories in Melbourne, Australia. In 1953 and 1954, a series of fatal accidents involving the de Havilland Comet prompted the grounding of the entire fleet pending an investigation. Dr. Warren, a chemist specializing in aircraft fuels, was involved in a professional committee discussing the possible causes. Since there had been neither witnesses nor survivors, Dr. Warren conceived of a crash-survivable method to record the flight crew's conversation (and other pre-crash data), reasoning they would greatly assist in determining a cause and enabling the prevention of future, avoidable accidents of the same type.

Despite his 1954 report entitled "A Device for Assisting Investigation into Aircraft Accidents" and a 1957 prototype FDR called "The ARL Flight Memory Unit", aviation authorities from around the world were largely uninterested. This changed in 1958 when Sir Robert Hardingham, the Secretary of the British Air Registration Board, visited the ARL and was introduced to Warren.



1962 ARL encoder/recorder units by Lane Sear and Wally Boswell.

The Aeronautical Research Laboratory allocated Dr. Warren an engineering team to develop the prototype to airborne stage. The team, consisting of electronics engineers Lane Sear, Wally Boswell and Ken Fraser developed a working design incorporating a fire and shockproof case, a reliable system for encoding and recording aircraft instrument readings and voice on one wire, and a ground-based decoding device. The ARL system became the "Red Egg", made by the British firm of S. Davall & Son. The "Red Egg" got its name from its' shape and bright red color. In 1960, after the crash of an aircraft at Mackay (Queensland), the inquiry judge strongly recommended that flight recorders be installed in all airliners. Australia then became the first country in the world to make cockpit-voice recording compulsory.

The origin of the term "Black Box" is uncertain. One explanation comes from the early film-based design of flight data recorders, which required the inside of the recorder to be perfectly dark to prevent light leaks from corrupting the record, as in a photographer's darkroom. Another explanation of the "black box" name came from a meeting about Warren's "Red Egg", when afterwards a journalist told Dr. Warren, *"This is a wonderful black box."* The unit itself was based on an EMI *Minifon* wire recorder (originally a 1950's espionage gadget from the west-German manufacterer *Protona Monske*) fitted into a perspex box firmly screwed together.

Design

The design of today's FDR is governed by the internationally recognized standards and recommended practices relating to flight recorders which are contained in ICAO Annex 6 which makes reference to industry crashworthiness and fire protection specifications such as those to be found in the European Organisation for Civil Aviation Equipment documents EUROCAE ED55, ED56 fiken A and ED112 (Minimum Operational Performance Specification for Crash Protected Airborne Recorder Systems). In the United States, the Federal Aviation Administration (FAA) regulates all aspects of U.S. aviation, and cites design requirements in their Technical Standard Order, based on the EUROCAE documents (as do the aviation authorities of many other countries).

After the crash of Gol Transportes Aéreos Flight 1907, Brazilian Air Force personnel recover the flight data recorder of PR-GTD, the Boeing 737-8EH used for the flight, in the Amazon Rainforest in Mato Grosso, Brazil.

Currently, EUROCAE specifies that a recorder must be able to withstand an acceleration of 3400 *g* (33 km/s²) for 6.5 milliseconds. This is roughly equivalent to an impact velocity of 270 knots (310 mph) and a deceleration or crushing distance of 450 cm. Additionally, there are requirements for penetration resistance, static crush, high and low temperature fires, deep sea pressure, sea water immersion, and fluid immersion.

Modern day FDRs receive inputs via specific data frames from the FDAU units. They record significant flight parameters, including the control and actuator positions, engine information and time of day. There are 88 parameters required as a minimum under current U.S. federal regulations (only 29 were required until 2002), but some systems monitor many more variables. Generally each parameter is recorded a few times per second, though some units store "bursts" of data at a much higher frequency if the data begins to change quickly. Most FDRs record approximately 17–25 hours worth of data in a continuous loop. It is required by regulations, that an FDR verification check (readout) is performed annually, in order to verify that all mandatory parameters are recorded.

This has also given rise to flight data monitoring programs, whereby flights are analyzed for optimum fuel consumption and dangerous flight crew habits. The data from the FDR is transferred, in situ, to a solid state recording device and then periodically analyzed with some of the same technology used for accident investigations.

FDRs are usually located in the rear of the aircraft, typically in the tail. In this position, the entire front of the aircraft is expected to act as a "crush zone" to reduce the shock that reaches the recorder. Also, modern FDRs are typically double wrapped, in strong corrosion-resistant stainless steel or titanium, with high-temperature insulation inside. They are usually bright orange. They are designed to emit a locator beacon for up to 30 days, and can operate immersed to a depth of up to 6,000 meters (20,000 ft).

Future devices

Since the recorders can sometimes be crushed into unreadable pieces, or even located in deep water, some modern units are self-ejecting (taking advantage of kinetic energy at impact to separate themselves from the aircraft) and also equipped with radio and sonar beacons to aid in their location.

Alternatively, other aircraft such as the Space Shuttle Orbiter do not possess an FDR but instead use down-links to transfer such data. This kind of system could potentially see wider use in aviation in modified form.

On 19 July 2005, the *Safe Aviation and Flight Enhancement Act of 2005* was introduced and referred to the Committee on Transportation and Infrastructure of the U.S. House of Representatives. This bill would require installation of a second cockpit voice recorder, digital flight data recorder system and emergency locator transmitter that utilizes combination deployable recorder technology in each commercial passenger aircraft, currently required to carry each of those recorders. The deployable recorder system would be ejected from the rear of the aircraft at the moment of an accident. The bill was referred to the Subcommittee on Aviation and has not progressed since.

Chapter 12

Head-Up Display

HUD of an F/A-18C

A **head-up display** or **heads-up display** (**HUD**) is any transparent display that presents data without requiring users to look away from their usual viewpoints. The origin of the name stems from the pilots being able to view information with heads "up" and looking forward, instead of angled down looking at lower instruments.

Although they were initially developed for military aviation, HUDs are now used in commercial aircraft, automobiles, and other applications.

History

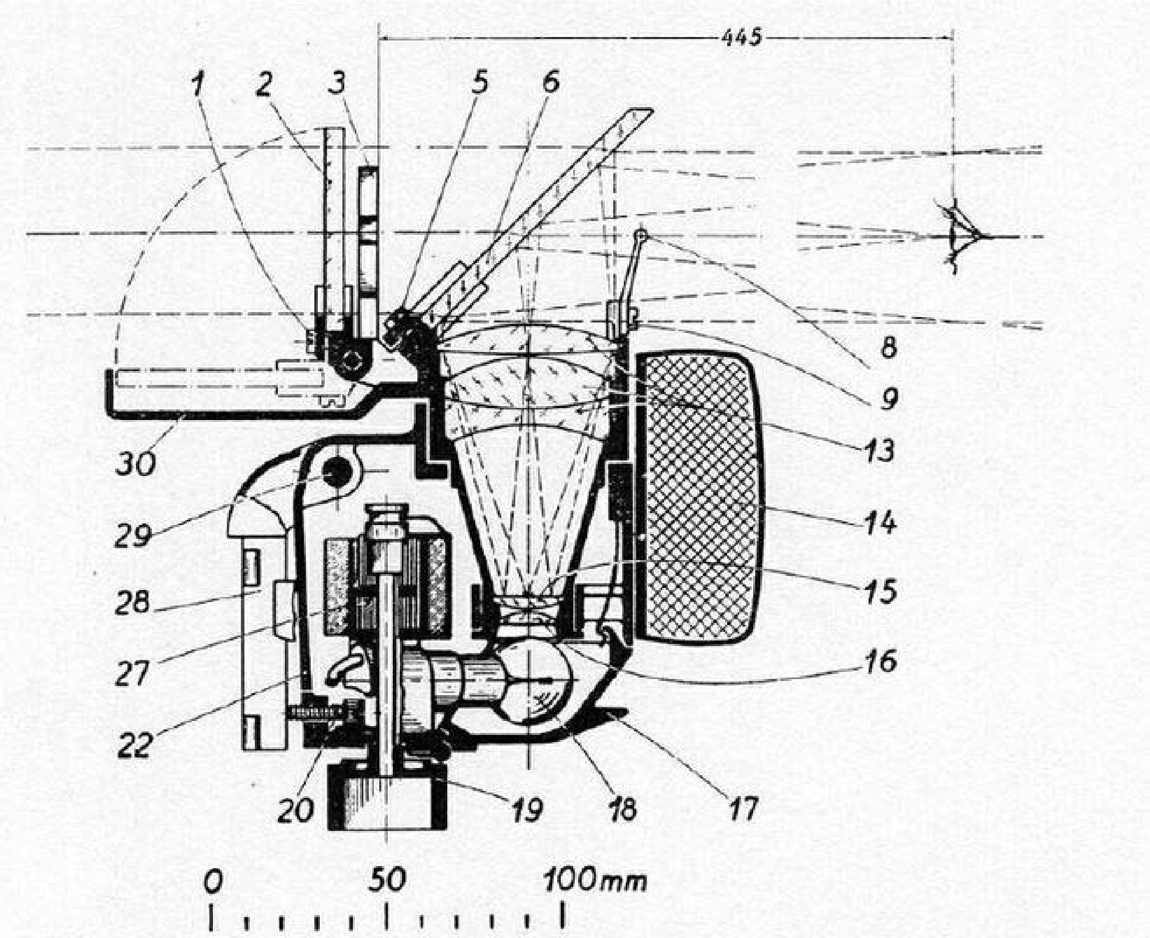
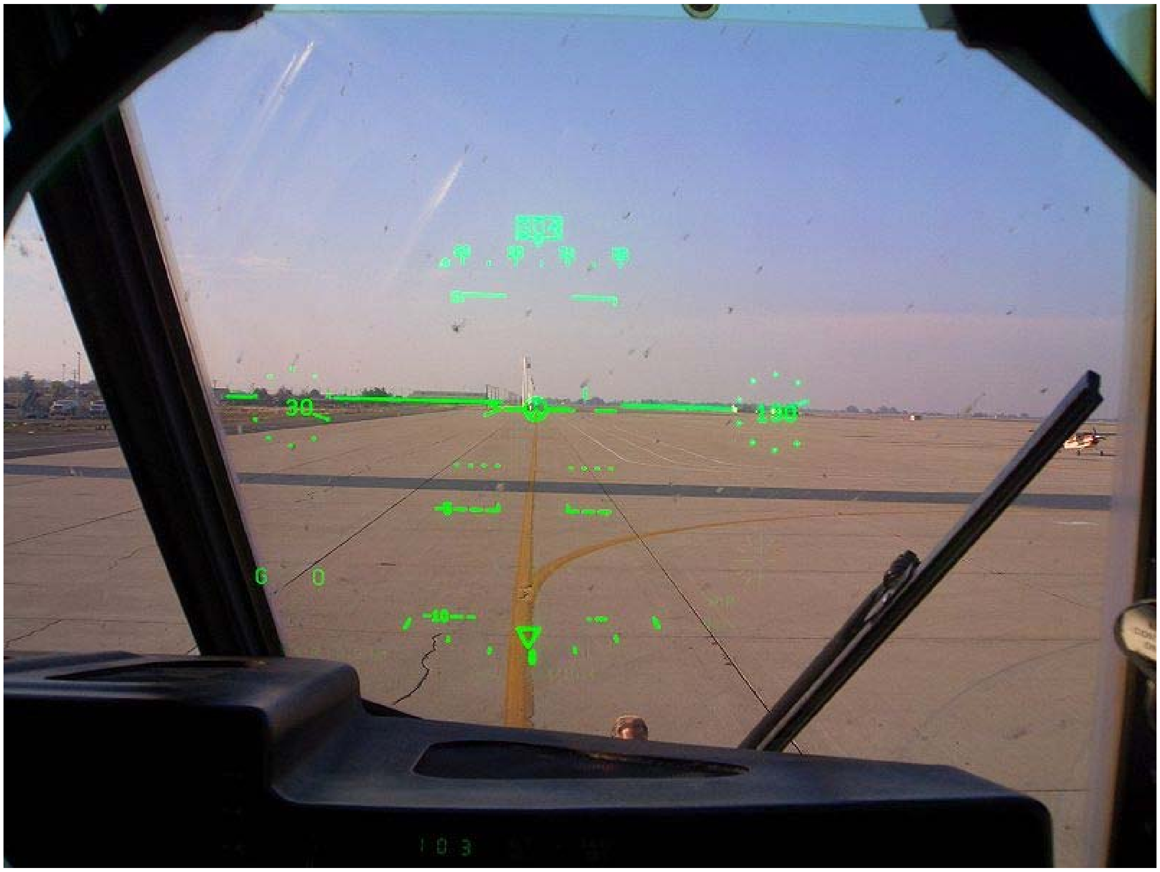


Abb. 4

Längsſchnitt des Revi C/12 A

Longitudinal cross-section of a German Revi C12/A, built in 1937



Copilot's HUD of a C-130J

The first HUDs were derived from static gun sight technology for military fighter aircraft. Rudimentary HUDs projected a "pipper" to aid aircraft gun aiming. As HUDs advanced, more (and more complex) information was added. HUDs soon displayed computed gunnery solutions, using aircraft information such as airspeed and angle of attack, thus greatly increasing the accuracy pilots could achieve in air to air battles. An early example of what would now be termed a head-up display was the Projector System of the British AI Mk VIII air interception radar fitted to some de Havilland Mosquito night fighters, where the radar display was projected onto the aircraft's windscreen along with the artificial horizon, allowing the pilots to perform interceptions without taking their eyes from the windscreen.

HUD technology was next advanced in the Buccaneer, the prototype of which first flew on 30 April 1958. The aircraft's design called for an attack sight that would provide navigation and weapon release information for the low level attack mode. There was fierce competition between supporters of the new HUD design and supporters of the old electro-mechanical gunsight, with the HUD being described as a radical, even foolhardy option. The Air Arm branch of the Ministry sponsored the development of a Strike Sight. The Royal Aircraft Establishment (RAE) designed the equipment, it was built by Cintel, and the system was first integrated in 1958. The Cintel HUD business was taken over by Elliott Flight Automation and the Buccaneer HUD was manufactured and further developed continuing up to a Mark III version with a total of 375 systems made; it was given a `fit and forget' title by the Royal Navy and it was still in service nearly 25 years later. BAE Systems thus has a claim to the world's first Head Up Display in operational service.

In the United Kingdom, it was soon noted that pilots flying with the new gun-sights were becoming better at piloting their aircraft. At this point, the HUD expanded its purpose beyond weapon aiming to general piloting. In the 1960s, French test-pilot Gilbert Klopfstein created the first modern HUD and a standardized system of HUD symbols so that pilots would only have to learn one system and could more easily transition between aircraft. The modern HUD used in instrument flight rules approaches to landing was developed in 1975. Klopfstein pioneered HUD technology in military fighter jets and helicopters, aiming to centralize critical flight data within the pilot's field of vision. This approach sought to increase the pilot's scan efficiency and reduce "task saturation" and information overload.

Use of HUDs then expanded beyond military aircraft. In the 1970s, the HUD was introduced to commercial aviation, and in 1988, the Oldsmobile Cutlass Supreme became the first production car with a head-up display.

Until a few years ago, the Embraer 190 and Boeing 737 New Generation Aircraft (737-600,700,800, and 900 series) were the only commercial passenger aircraft available with HUDs. However, the technology is becoming more common with aircraft such as the Canadair RJ, Airbus A318 and several business jets featuring the displays. HUDs have become standard equipment on the Boeing 787. Furthermore, the Airbus A320, A330, A340 and A380 families are currently undergoing the certification process for a HUD. HUDs are also added to the Space Shuttle orbiter.

Types

Helmet mounted displays (*HMD*) are technically a form of HUD, the distinction being that they feature a display element that moves with the orientation of the users' heads relative the airframe.

Many modern fighters (such as F/A-18, F-22, Eurofighter) use both a HUD and HMD concurrently. The F-35 Lightning II was designed without a HUD, relying solely on the HMD, making it the first modern military fighter not to have a fixed HUD.

Generations

HUDs are split into four generations reflecting the technology used to generate the images.

- First Generation—Use a CRT to generate an image on a phosphor screen, having the disadvantage of the phosphor screen coating degrading over time. The majority of HUDs in operation today are of this type.

- Second Generation—Use a solid state light source, for example LED, which is modulated by an LCD screen to display an image. These systems do not fade or require the high voltages of first generation systems. These systems are on commercial aircraft.
- Third Generation—Use optical waveguides to produce images directly in the combiner rather than use a projection system.
- Fourth Generation—Use a scanning laser to display images and even video imagery on a clear transparent medium.

Newer micro-display imaging technologies are being introduced, including liquid crystal display (LCD), liquid crystal on silicon (LCoS), digital micro-mirrors (DMD), and organic light-emitting diode (OLED).

Design factors

There are several factors that engineers must consider when designing a HUD:

- field of vision—Because the human eyes are separated, each eye receives a different image. To prevent a pilots' eyes from having to change focus between the outside world and the display of the HUD, the display is collimated (focused at infinity). In automobiles the display is generally focused near the distance to the bumper.
- eyebox—displays can only be viewed while the viewers' eyes are within a three-dimensional area called the *head motion box* or *eyebox*. Modern HUD eyeboxes are usually about 5 by 3 by 6 inches. This allows viewers some freedom of head movement. It also allows pilots the ability to view the entire display as long as one of their eyes is inside the eyebox.
- luminance/contrast—displays must be adjustable in luminance and contrast to account for ambient lighting, which can vary widely (e.g., from the glare of bright clouds to moonless night approaches to minimally lit fields).
- display accuracy—aircraft HUD components must be very accurately aligned with the aircraft's three axes – a process called *boresighting* – so that displayed data conforms to reality typically with an accuracy of ±7.0 milliradians. In this case the word "conform" means, "when an object is projected on the combiner and the actual object is visible, they will be aligned". This allows the display to show the pilot exactly where the artificial horizon is, as well as the aircraft's projected path with great accuracy. When Enhanced Vision is used, for example, the display of runway lights must be aligned with the actual runway lights when the real lights become visible. Boresighting is done during the aircraft's building process and can also be performed in the field on many aircraft.
- compatibility—HUD components must be compatible with other avionics, displays, etc.

Components

A typical HUD contains three primary components: a *combiner*, *projector unit*, and video generation computer.

The combiner is the part of the unit located directly in front of the pilot, providing the surface onto which the information is projected for view. Combiners can be concave or flat, and have a special coating that reflects the monochromatic light projected onto it from the projector unit while allowing all other wavelengths of light to pass through. On some aircraft the combiners are easily removable (or can be rotated out of the way) by aircrew.

The projection unit projects the image onto the combiner for the pilot to view. In early HUDs, this was done using refraction, although modern HUDs use reflection. Projection units use Cathode Ray Tubes, light emitting diodes, or liquid crystal displays to project the image. Projection units can be either below (as with most fighter aircraft) or above (as with transport/commercial aircraft) combiners.

The computer is usually located with the other avionics equipment and provides the interface between the HUD (i.e. the projection unit) and the systems/data to be displayed. On aircraft, these computers are typically dual independent redundant systems. They receive input directly from the sensors (pitot-static, gyroscopic, navigation, etc.) aboard the aircraft and perform their own computations rather than receiving previously computed data from the flight computers. Computers are integrated with the aircraft's systems and allow connectivity onto several different data buses such as the ARINC 429, ARINC 629, and MIL-STD-1553.

Aircraft

Displayed data

Typical aircraft HUDs display airspeed, altitude, a horizon line, heading, turn/bank and slip/skid indicators. These instruments are the minimum required by 14 CFR Part 91.

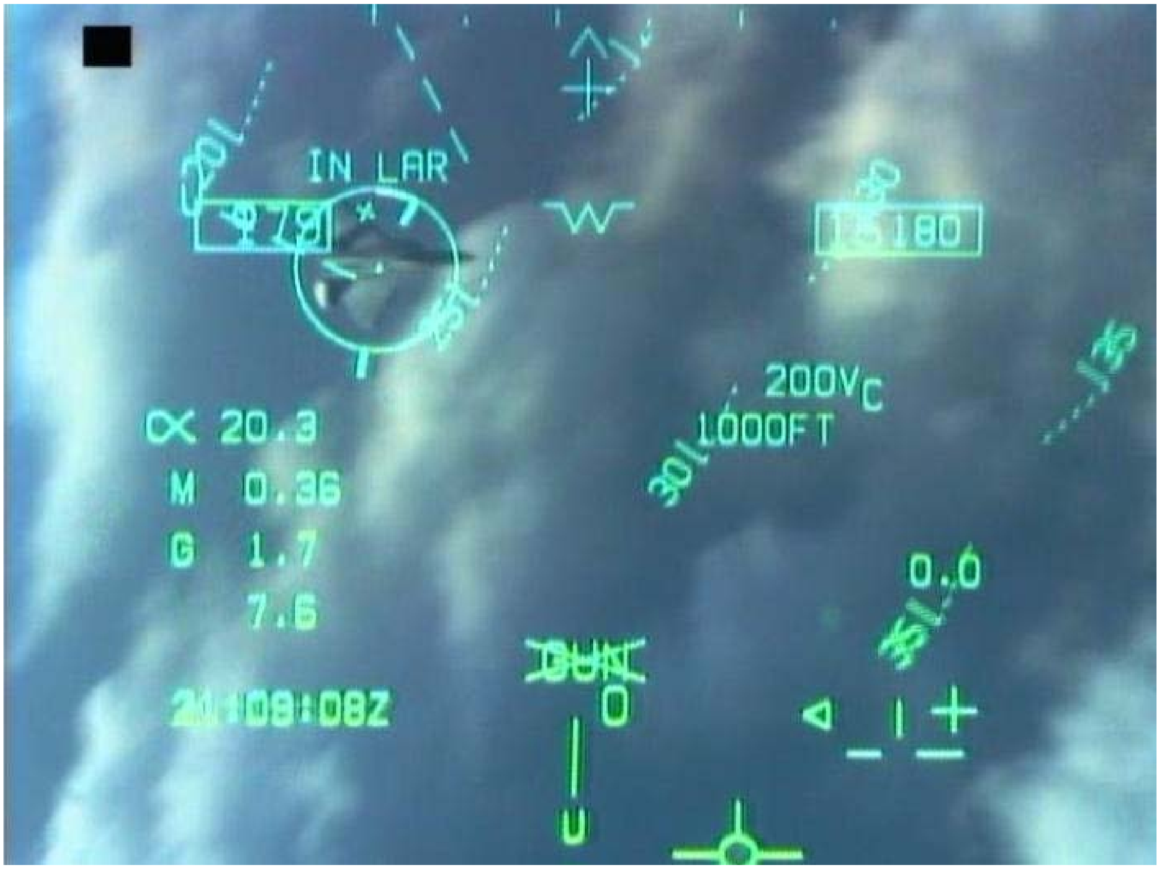
Other symbols and data are also available in some HUDs:

- *boresight* or *waterline* symbol—is fixed on the display and shows where the nose of the aircraft is actually pointing.
- *flight path vector (FPV)* or *velocity vector* symbol—shows where the aircraft is actually going, the sum of all forces acting on the aircraft. For example, if the aircraft is pitched up but is losing energy, then the FPV symbol will be below the horizon even though the boresight symbol is above the horizon. During approach and landing, a pilot can fly the approach by keeping the FPV symbol at the desired descent angle and touchdown point on the runway.
- *acceleration indicator* or *energy cue*—typically to the left of the FPV symbol, it is above it if the aircraft is accelerating, and below the FPV symbol if decelerating.

- *angle of attack indicator*—shows the wing's angle relative to the airflow, often displayed as *"α"*.
- navigation data and symbols—for approaches and landings, the flight guidance systems can provide visual cues based on navigation aids such as an Instrument Landing System or augmented Global Positioning System such as the Wide Area Augmentation System. Typically this is a circle which fits inside the flight path vector symbol. Pilots can fly along the correct flight path by "flying to" the guidance cue.

Since being introduced on HUDs, both the FPV and acceleration symbols are becoming standard on head-down displays (HDD). The actual form of the FPV symbol on an HDD is not standardized but is usually a simple aircraft drawing, such as a circle with two short angled lines, (180 ± 30 degrees) and "wings" on the ends of the descending line. Keeping the FPV on the horizon allows the pilot to fly level turns in various angles of bank.

Military aircraft specific applications



FA-18 HUD while engaged in a dogfight

In addition to the generic information described above, military applications include weapons system and sensor data such as:

- *target designation (TD)* indicator—places a cue over an air or ground target (which is typically derived from radar or inertial navigation system data).
- V_c—closing velocity with target.
- *Range*—to target, waypoint, etc.
- *Launch Acceptability Region (LAR)*—displays when an air-to-air or air-to-ground weapon can be successfully launched to reach a specified target.
- *weapon seeker* or sensor line of sight—shows where a seeker or sensor is pointing.
- *weapon status*—includes type and number of weapons selected, available, arming, etc.

VTOL/STOL approaches and landings

During the 1980s, the military tested the use of HUDs in vertical take off and landings (VTOL) and short take off and landing (STOL) aircraft. A HUD format was developed at NASA Ames Research Center to provide pilots of V/STOL aircraft with complete flight guidance and control information for Category-IIIC terminal-area flight operations. This includes a large variety of flight operations, from STOL flights on land-based runways to VTOL operations on aircraft carriers. The principal features of this display format are the integration of the flightpath and pursuit guidance information into a narrow field of view, easily assimilated by the pilot with a single glance, and the superposition of vertical and horizontal situation information. The display is a derivative of a successful design developed for conventional transport aircraft.

Civil aircraft specific applications

The cockpit of NASA's Gulfstream GV with a synthetic vision system display. Several different HUD elements are visible, including the combiner in front of the pilot. The green 'glare' in the lower right corner of the combiner is a result of backscatter of off-axis light from the projection unit, as well as reflection from ambient light in the flight deck. Because the combiner has a pronounced vertical and horizontal curve to help focus the image, compensation is applied to the display symbols to make them appear flat when projected onto the curved surface. When not in use, this combiner can swing up and lock in a stowed position. The Projector Unit in the Gulfstream GV image would be directly above the pilot's head. In smaller aircraft the design of the projection unit can present interesting spacing and placement issues, as room must be left for the pilot not only when normally seated but also during turbulence and when getting in and out of the seat.

The use of head-up displays allows commercial aircraft substantial flexibility in their operations. Systems have been approved which allow reduced-visibility takeoffs and landings, as well as full Category IIIc landings. Studies have shown that the use of a HUD during landings decreases the lateral deviation from centerline in all landing conditions, although the touchdown point along the centerline is not changed.

Enhanced flight vision systems

In more advanced systems, such as the FAA-labeled *Enhanced Flight Vision System*, a real-world visual image can be overlaid onto the combiner. Typically an infrared camera (either single or multi-band) is installed in the nose of the aircraft to display a conformed image to the pilot. *EVS Enhanced Vision System* is an industry accepted term which the FAA decided not to use because "the FAA believes [it] could be confused with the system definition and operational concept found in 91.175(l) and (m)" In one EVS installation, the camera is actually installed at the top of the vertical stabilizer rather than "as close as practical to the pilots eye position". When used with a HUD however, the camera must be mounted as close as possible to the pilots eye point as the image is expected to "overlay" the real world as the pilot looks through the combiner.

"Registration," or the accurate overlay of the EVS image with the real world image, is one feature closely examined by authorities prior to approval of a HUD based EVS. This is because of the importance of the HUD matching the real world.

While the EVS display can greatly help, the FAA has only relaxed operating regulations so an aircraft with EVS can perform a CATEGORY I approach to CATEGORY II minimums. In all other cases the flight crew must comply with all "unaided" visual restrictions. (For example if the runway visibility is restricted because of fog, even though EVS may provide a clear visual image it is not appropriate (or actually legal) to maneuver the aircraft using only the EVS below 100' agl.)

Synthetic vision systems

A synthetic vision system display

HUD systems are also being designed to utilize a synthetic vision system (SVS), which use terrain databases to create realistic and intuitive views of the outside world.

In SVS image to the right, immediately visible indicators include the airspeed tape on the left, altitude tape on the right, and turn/bank/slip/skid displays at the top center. The boresight symbol (-v-) is in the center and directly below that is the flight path vector symbol (the circle with short wings and a vertical stabilizer). The horizon line is visible running across the display with a break at the center, and directly to the left are the numbers at ±10 degrees with a short line at ±5 degrees (The +5 degree line is easier to see) which, along with the horizon line, show the pitch of the aircraft.

The aircraft in the image is wings level (i.e. the flight path vector symbol is flat relative to the horizon line and there is zero roll on the turn/bank indicator). Airspeed is 140 knots, altitude is 9450 feet, heading is 343 degrees (the number below the turn/bank indicator). Close inspection of the image shows a small purple circle which is displaced from the Flight Path Vector slightly to the lower right. This is the guidance cue coming from the Flight Guidance System. When stabilized on the approach, this purple symbol should be centered *within* the FPV.

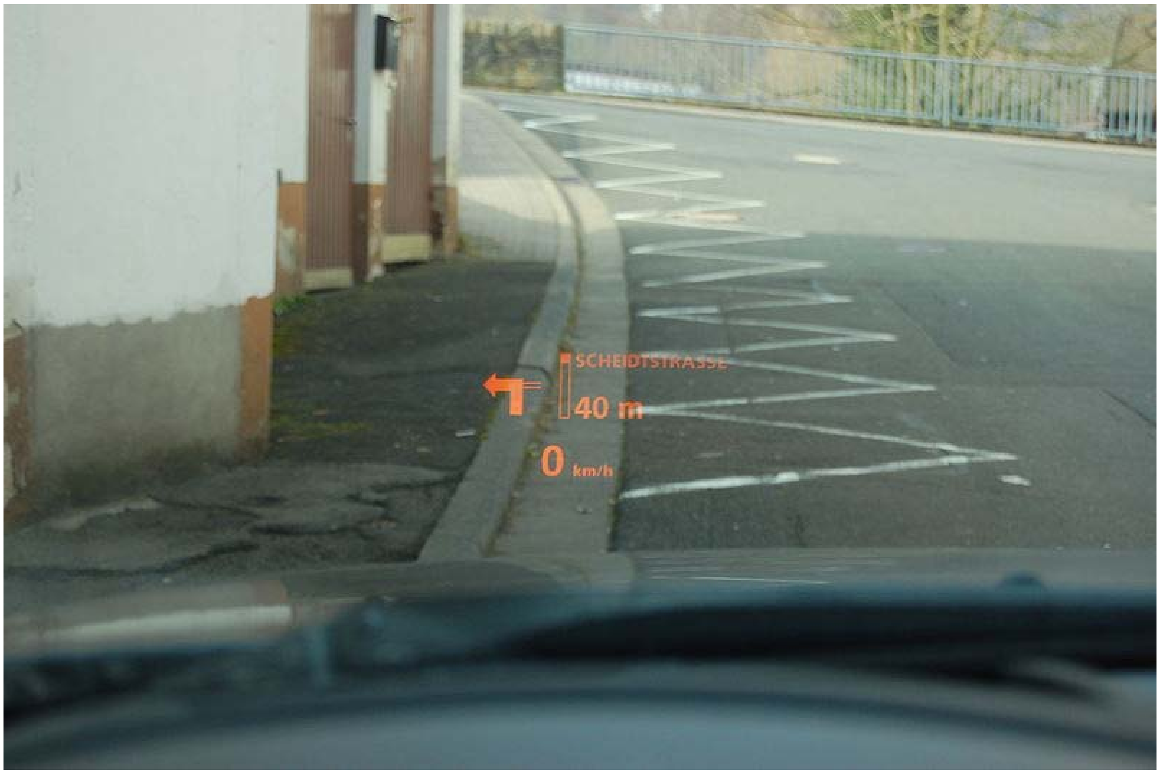
The terrain is entirely computer generated from a high resolution terrain database.

In some systems, the SVS will calculate the aircraft's current flight path, or possible flight path (based on an aircraft performance model, the aircraft's current energy, and surrounding terrain) and then turn any obstructions red to alert the flight crew. Such a system could have prevented the crash of American Airlines Flight 965 in 1995.

On the left side of the display is an SVS-unique symbol, with the appearance of a purple, dimishing sideways ladder, and which continues on the right of the display. The two lines define a "tunnel in the sky". This symbol defines the desired trajectory of the aircraft in three dimensions. For example, if the pilot had selected an airport to the left, then this symbol would curve off to the left and down. If the pilot keeps the flight path vector alongside the trajectory symbol, the craft will fly the optimum path. This path would be based on information stored in the Flight Management System's data base and would show the FAA-approved approach for that airport.

The tunnel in the sky can also greatly assist the pilot when more precise four dimensional flying is required, such as the decreased vertical or horizontal clearance requirements of RNP. Under such conditions the pilot is given a graphical depiction of where the aircraft should be and where it should be going rather than the pilot having to mentally integrate altitude, airspeed, heading, energy and longitude and latitude to correctly fly the aircraft.

Automobiles



HUD in a BMW E60

HUD in a Pontiac Bonneville showing a speed of 47 mph

General Motors began using head-up displays in 1988 with the first color display appearing in 2001 on the Corvette. In 2003, BMW became the first European manufacturer to offer HUDs. The displays are becoming increasingly available in production cars, and usually offer speedometer, tachometer, and navigation system displays. Night vision information is also displayed via HUD on certain General Motors, Honda, Toyota and Lexus vehicles. Other manufactures such as Citroën, Saab, and Nissan currently offer some form of HUD system. Motorcycle helmet HUDs are also commercially available.

Add-on HUD systems also exist, projecting the display onto a glass combiner mounted on the windshield. These systems have been marketed to police agencies for use with in-vehicle computers.

Developmental / experimental uses

HUDs have been proposed or are being experimentally developed for a number of other applications. In the military, a HUD can be used to overlay tactical information such as the output of a laser rangefinder or squadmate locations to infantrymen. A prototype HUD has also been developed that displays information on the inside of a swimmer's goggles or of a scuba diver's mask. A group of Electrical Engineering students from the University of Massachusetts Amherst are integrating technologies in order to develop an affordable Personal Head-Up Display. One such design is a HUD in skiing goggles.

HUD systems that project information directly onto the wearer's retina with a low-powered laser (virtual retinal display) are also in experimentation. This kind of head-up display has been common in science fiction movies for decades, notably in Terminator and RoboCop.

Chapter 13

Annunciator Panel

An **annunciator panel** is a group of lights used as a central indicator of status of equipment or systems in an aircraft, industrial process, building or other installation. Usually the annunciator panel includes a main warning lamp or audible signal to draw the attention of operating personnel to the annunciator panel for abnormal events or conditions.

Aviation

(above) The annunciator panel of a Cessna 441 aircraft. The illuminated annunciators are those that are normally lit when the engines are not running, plus one annunciating that the aircraft's door is not locked. (below) Close-up view of the left module of the annunciator panel in 'test' mode

In the aircraft industry, **annunciator panels** are groupings of **annunciator lights** that indicate status of the aircraft's subsystems. The lights are usually accompanied with a test switch, which when pressed illuminates all the lights to confirm they are in working order. More advanced modern aircraft replaces these with the integrated electronic Engine Indicating and Crew Alerting System or Electronic Centralised Aircraft Monitor.

On this aircraft overhead panel, the pilot is pressing the test switch. You can also see how the lights are grouped together with their associated systems into various panels of lights.

The following colours are normally utilised with the following meanings:

- Red - Warning, this systems condition is critical and requires immediate attention (such as an engine fire, hydraulic pump failure)
- Orange/Yellow - Caution, this system requires timely attention or may do so in the future (ice detected, fuel imbalance)
- Green - Advisory/Indication, a system is in use or ready for operation (such as landing gear down and locked, APU operating)
- White/blue - Advisory/Indication, a system is in use (seatbelt signs on, anti-ice system in-use, landing lights on)

On occasion, the annunciator panel will display warnings or cautions that are not necessarily indicative of a problem; for example, a Cessna 172 on its after-landing roll will often flicker the "Volts" warning simply due to the idle throttle position and therefore the lower voltage output of the alternator to the aircraft's electrical system.

More complicated aircraft will feature "Master Warning" and "Master Caution" lights/switches. In the event of any red or yellow annunciator being activated, the yellow or red master light, usually located elsewhere in the pilots line of sight will illuminate, in most installations they flash and an audible alert will accompany them. These "masters" will not stop flashing until they have been acknowledged, usually by pressing the light itself and in some cases the audible alert will also continue until this acknowledgement.

In this aircraft cockpit, the annunciator panel is clearly visible in the centre of the panel (just to the left and below the big red handle/lever), displaying a variety of warnings of differing severity. Directly below the windscreen area, on both the left and right side of the picture, is a large red light with a large yellow one below it. These are the master warning and master caution lights/switches.

Process control

In industrial process control, an annunciator panel is a system to alert operators of alarm conditions in the plant. Multiple back-lit windows are provided, each engraved with the name of a process alarm. Lamps in each window are controlled by hard-wired switches in the plant, arranged to operate when a process condition enters an abnormal state (such as high temperature, low pressure, loss of cooling water flow, or many others). Single point or multipoint alarm logic modules operate the window lights based on a preselected ISA 18.1 or custom sequence.

In one common alarm sequence, the light in a window will flash and a bell or horn will sound to attract the operator's attention when the alarm condition is detected. The operator can silence the alarm with a button, and the window will remain lit as long as the process is in the alarm state. When the alarm clears (process condition returns to normal), the lamps in the window go out.

Annunciator panels were relatively costly to install in a plant because they had dedicated wiring to the alarm initiating devices in the process plant. Since incandescent lamps were used, a lamp test button was always provided to allow early detection of failed lamps. Modern electronic distributed control systems usually require less wiring since the process signals can be monitored within the control system, and the engraved windows are replaced by alaphanumeric displays on a computer monitor.

Behavior of alarm systems, and colors used to indicate alarms, are standardized. Standards such as ISA 18.1 or EN 60073 simplify purchase of systems and training of operators by giving standard alarm sequences.

Obsolescence and revival

The introduction of computer monitor based control systems during the 1980s and 1990s saw a wholesale absorption of alarm window displays on to the computer screen. This created a down-turn in the sales of the conventional Alarm Annunciator systems and many of the companies manufacturing these alarm annunciator products were either sold off or went out of business. This has left today a major obsolescence support problem for customers who are still using these Alarm Annunciator systems as part of their safety systems.

Over the last five years the Alarm Annunciator has seen a resurgence in popularity especially for use in IEC61508 SIL 1 and SHE (Safety Health and Environmental) alarm monitoring applications. The modern trend is to identify critical alarms and return them from the computer screen to discrete alarm windows. This is being done for two reasons. Firstly, alarm annunciators offer pattern recognition to the operators in the form of LED alarm fascias instead of just providing an exhaustive list of alarms and events which the operators have to scroll through and in some instances alarms can be overlooked. Secondly, the analysis of plant failure modes is leading to the separation of critical alarm monitoring and process control systems for safety reasons.

Discrete annunciators vs SCADA alarm systems

Some time ago SCADA systems were considered the preferred alternative to discrete annunciators. A software-based solution, with almost endless ability to analyze, present and process alarms, has the potential for replacing discrete alarms switches altogether.

However, software carries its own reliability risks. Reliance on a software program to trigger an alarm assumes that the analog signal, the programmer's logic code and HMI, the PLC and/or PC running the programs, and the interaction between all of the above, are all entirely trustworthy. This is exacerbated by frequently changing computer hardware & firmware platforms and the need to modify existing software.

Fire alarm panel

In large buildings, a central fire alarm annunciator panel is located where it is accessible to fire-fighting crews. The annunciator panel will indicate the zone and approximate physical location of the source of a fire alarm in the building. The annunciator will also include lamps and audible warning devices to indicate failures of alarm circuits. In a large building such as an office tower or hotel, the fire annunciator may also be associated with a control panel for building ventilation systems, and may also include emergency communication systems for the building.

Chapter 14

Avionics

Avionics is a portmanteau of "aviation" and "electronics". It comprises electronic systems for use on aircraft, artificial satellites and spacecraft, comprising communications, navigation and the display and management of multiple systems. It also includes the hundreds of systems that are fitted to aircraft to meet individual roles, these can be as simple as a search light for a police helicopter or as complicated as the tactical system for an Airborne Early Warning platform.

History

The term avionics is believed to have been coined by journalist Philip J. Klass. Avionics was pioneered in the 1970s, driven by military need rather than civil airliner development. Military aircraft had become flying sensor platforms, and making large amounts of electronic equipment work together had become the new challenge. Today, avionics as used in military aircraft almost always forms the biggest part of any development budget. Aircraft like the F-15E and the now retired F-14 have roughly 80 percent of their budget spent on avionics. Most modern helicopters now have budget splits of 60/40 in favour of avionics.

The civilian market has also seen a growth in cost of avionics. Flight control systems (fly-by-wire) and new navigation needs brought on by tighter airspaces, have pushed up development costs. The major change has been the recent boom in consumer flying. As more people begin to use planes as their primary method of transportation, more elaborate methods of controlling aircraft safely in these high restrictive airspaces have been invented.

Main categories

Aircraft avionics

The cockpit of an aircraft is a major location for avionic equipment, including control, monitoring, communication, navigation, weather, and anti-collision systems. The majority of aircraft drive their avionics using 14 or 28 volt DC electrical systems; however, large, more sophisticated aircraft (such as airliners or military combat aircraft) have AC systems operating at 400 Hz,& 115 volt rather than the more common 50 and

60 Hz of North American home electrical devices. There are several major vendors of flight avionics, including Honeywell (which now owns Bendix/King, Baker Electronics, Allied Signal, etc..]), Rockwell Collins, Thales Group, Garmin, Avidyne Corporation, and Narco Avionics.

Communications

Communications connect the flight deck to the ground, and the flight deck to the passengers. On board communications are provided by public address systems and aircraft intercoms.

The VHF aviation communication system works on the Airband of 118.000 MHz to 136.975 MHz. Each channel is spaced from the adjacent by 8.33 kHz.And VHF is also used for line of sight communication as, aircraft to aircraft , aircraft to atc for short distances.There are three VHF sys. Amplitude Modulation (AM) is used. The conversation is performed by simplex mode. Aircraft communication can also take place using HF (especially for trans-oceanic flights) or satellite communication.

Navigation

Navigation is the determination of position and direction on or above the surface of the Earth. Avionics can use satellite-based systems (such as GPS and WAAS), ground-based systems (such as VOR or LORAN), or any combination thereof. Older avionics required a pilot or navigator to plot the intersection of signals on a paper map to determine an aircraft's location; modern systems calculate the position automatically and display it to the flight crew on moving map displays.

Monitoring

Glass cockpits started to come into being with the Gulfstream G-IV private jet in 1985. Display systems display sensor data that allows the aircraft to fly safely. Much information that used to be displayed using mechanical gauges appears on electronic displays in newer aircraft.

Aircraft flight control systems

Airplanes and helicopters have means of automatically controlling flight. They reduce pilot workload at important times (like during landing, or in hover), and they make these actions safer by 'removing' pilot error. The first simple auto-pilots were used to control heading and altitude and had limited authority on things like thrust and flight control surfaces. In helicopters, auto stabilization was used in a similar way. The old systems were electromechanical in nature until very recently.

The advent of fly by wire and electro actuated flight surfaces (rather than the traditional hydraulic) has increased safety. As with displays and instruments, critical devices which were electro-mechanical had a finite life. With safety critical systems, the software is very strictly tested.

Collision-avoidance systems

To supplement air traffic control, most large transport aircraft and many smaller ones use a TCAS (Traffic Alert and Collision Avoidance System), which can detect the location of nearby aircraft, and provide instructions for avoiding a midair collision. Smaller aircraft may use simpler traffic alerting systems such as TPAS, which are passive (they do not actively interrogate the transponders of other aircraft) and do not provide advisories for conflict resolution.

To help avoid collision with terrain, (CFIT) aircraft use systems such as ground-proximity warning systems (GPWS), radar altimeter being the key element in GPWS. One of the major weaknesses of (GPWS) is the lack of "look-ahead" information as it only provides altitude above terrain "look-down". In order to overcome such weakness, modern aircraft use the Terrain Awareness Warning System (TAWS).

Weather systems

Weather systems such as weather radar (typically Arinc 708 on commercial aircraft) and lightning detectors are important for aircraft flying at night or in Instrument meteorological conditions, where it is not possible for pilots to see the weather ahead. Heavy precipitation (as sensed by radar) or severe turbulence (as sensed by lightning activity) are both indications of strong convective activity and severe turbulence, and weather systems allow pilots to deviate around these areas.

Lightning detectors like the Stormscope or Strikefinder have become inexpensive enough that they are practical for light aircraft. In addition to radar and lightning detection, observations and extended radar pictures (such as NEXRAD) are now available through satellite data connections, allowing pilots to see weather conditions far beyond the range of their own in-flight systems. Modern displays allow weather information to be integrated with moving maps, terrain, traffic, etc. onto a single screen, greatly simplifying navigation.

Aircraft management Systems

There has been a progression towards centralized control of the multiple complex systems fitted to aircraft, including engine monitoring and management. Health and Usage Monitoring Systems (HUMS) are integrated with aircraft management computers to allow maintainers early warnings of parts that will need replacement.

The Integrated Modular Avionics concept proposes an integrated architecture with application software portable across an assembly of common hardware modules. It has been used in Fourth generation jet fighters and the latests generation of Airliners.

Mission or tactical avionics

Military aircraft have been designed either to deliver a weapon or to be the eyes and ears of other weapon systems. The vast array of sensors available to the military is used for whatever tactical means required. As with aircraft management, the bigger sensor platforms (like the E-3D, JSTARS, ASTOR, Nimrod MRA4, Merlin HM Mk 1) have mission management computers.

Police and EMS aircraft also carry sophisticated tactical sensors.

Military communications

While aircraft communications provide the backbone for safe flight, the tactical systems are designed to withstand the rigours of the battle field. UHF, VHF Tactical (30-88 MHz) and SatCom systems combined with ECCM methods, and cryptography secure the communications. Data links like Link 11, 16, 22 and BOWMAN, JTRS and even TETRA provide the means of transmitting data (such as images, targeting information etc.).

Radar

Airborne radar was one of the first tactical sensors. The benefit of altitude providing range has meant a significant focus on airborne radar technologies. Radars include Airborne Early Warning (AEW), Anti-Submarine Warfare (ASW), and even Weather radar (Arinc 708) and ground tracking/proximity radar.

The military uses radar in fast jets to help pilots fly at low levels. While the civil market has had weather radar for a while, there are strict rules about using it to navigate the aircraft.

Sonar

Dipping sonar fitted to a range of military helicopters allows the helicopter to protect shipping assets from submarines or surface threats. Maritime support aircraft can drop active and passive sonar devices (Sonobuoys) and these are also used to determine the location of hostile submarines.

Electro-Optics

Electro-optic systems include Forward Looking Infrared (FLIR), and Passive Infrared Devices (PIDS). These are all used to provide imagery to crews. This imagery is used for everything from Search and Rescue through to acquiring better resolution on a target.

ESM/DAS

Electronic support measures and defensive aids are used extensively to gather information about threats or possible threats. They can be used to launch devices (in some cases automatically) to counter direct threats against the aircraft. They are also used to determine the state of a threat and identify it.

Aircraft Networks

The avionics systems in military, commercial and advanced models of civilian aircraft are interconnected using an avionics databus. Common avionics databus protocols, with their primary application, include:

- Aircraft Data Network (ADN): Ethernet derivative for Commercial Aircraft
- Avionics Full-Duplex Switched Ethernet (AFDX): Specific implementation of ARINC 664 (ADN) for Commercial Aircraft
- ARINC 429: Generic Medium-Speed Data Sharing for Private and Commercial Aircraft
- ARINC 664
- ARINC 629: Commercial Aircraft (Boeing 777)
- ARINC 708: Weather Radar for Commercial Aircraft
- ARINC 717: Flight Data Recorder for Commercial Aircraft
- IEEE 1394b: Military Aircraft
- MIL-STD-1553: Military Aircraft
- MIL-STD-1760: Military Aircraft
- TTP - Time-Triggered Protocol: Boeing 787 Dreamliner, Airbus A380, Fly-By-Wire Actuation Platforms from Parker Aerospace
- TTEthernet - Time-Triggered Ethernet: NASA Orion Spacecraft

Police and Air Ambulance

Police and EMS aircraft (mostly helicopters) are now a significant market. Military aircraft are often now built with a role available to assist in civil disobedience. Police helicopters are almost always fitted with video/FLIR systems to allow them to track suspects. They can also be fitted with searchlights and loudspeakers.

EMS and police helicopters will be required to fly in unpleasant conditions, this may require more aircraft sensors, some of which were until recently considered purely for military aircraft.