EE43 SENSORS

MA LONG

Sino-european Institute of Aviation Engineering
Civil Aviation University of China

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Lecture Objectives

Objectives:

- This course is to provide the essential and advanced knowledge of SENSORs, especially sensors used in air data and inertial quantities measurements. Radio navigation and GNSS will also be mentioned here since they are considered to be SENSORs in aviation world. This course will go through the general sensors and aeronautic sensors, pay **attentation** to their difference.

Lecture Plan

Content:

- Introduction
  The basic idea of sensor, the airborne equipments and how the cockpits evolve in recent decades.
- Air data sensors and Air Data Computer (ADC).
  How do we describe the atmosphere? And by which way we calculate air data?
- Inertial sensors and system
  What are inertial sensors? And what are they used for?
- Radio navigation
  Basic ideas on VOR,DME,ADF...
- GPS/GNSS
  Basic ideas on GNSS(GPS).

Outline

Sensor

What is "SENSOR"?

- Sensor in general sense
  In more general technology world, "SENSOR" means:

  > *A 'sensor' is a device that measures a physical quantity and converts it into a 'signal' which can be read by an observer or by an instrument.*
  >
  > —*https://en.wikipedia.org/wiki/Sensor*

- Sensor in avionics
  VOR,ADF,DME,GPS,. . . , to provide navigation service

Sensor Examples

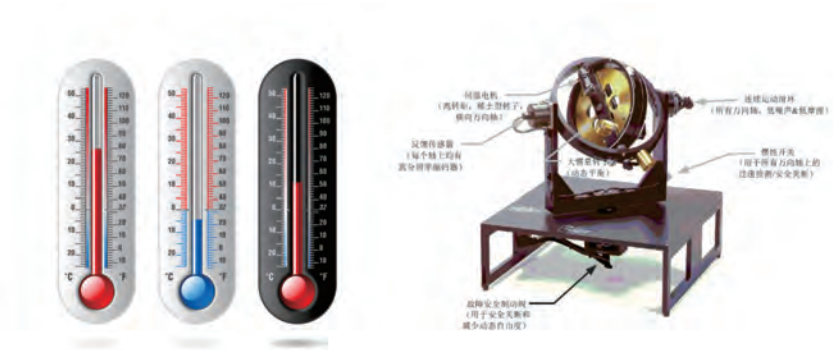


Fig. 1: Different type of sensors

Sensor Definition

Definition by Chinese government:

GB7665-1987

Fig. 2: Function description of sensor definition

Airborne Systems

Generally, the aircraft has the following systems:

- Control system
- Navigation system
- Surveillance system
- Communication system

With the evolution of the system, the cockpit also changes from time to time:

- Instruments evolution
- Organization

Outline

General Description of Flight Control

To effectively control the flight means the pilot will operate the lift force by controlling the engine power in certain attitude as long as the effective navigation is provided.

The pilot can control the flight through the following 2 ways:

- The attitude.
- The trajectory.

Control Variables

To control a flight in operation:

- Airspeed: IAS,CAS,TAS,V/S
- Attitude: roll,pitch,yaw
- Altitude
- ......

From the view of flight operation, "sensor" here must be used to precisely sense the actual state of the "control variables" .

Airspeed

Airspeed is the a critical flight variable, which can directly reflect the lift force and has impacts on the aircraft structures.

The instruments for airspeed measurements:

- Satitc-Pitot tube (airspeed indicator)

Fig. 3: Pitot tube

Attitude

Attitude is directly controlled by the pilot through the movement of control surface.

- Roll(bank),pitch,yaw
- Angle of sideslip (AOS)
- Angle of attack (AOA)

The sensors that can measure the above quantities are:

- Gyroscope based sensors
  - IRS, INS, AHRS, IMU...
- AOS/AOA sensors

Attitude

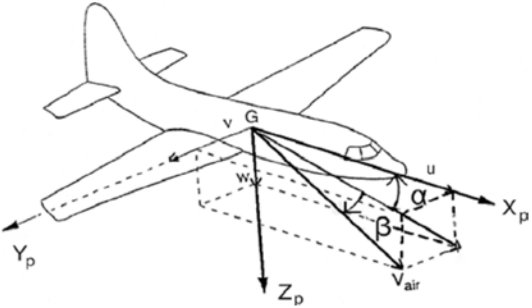


Fig. 4: Attitude,AOA and AOS

Altitude

Altitude could be measured by:

- Pitot-static tube or static ports
- GNSS
- Radio waves

In all phases of flight except landing and taking off, static ports will be responsible to provide the altitude information to the pilot.

Fig. 5: Static ports

Outline

CNS Concept

Airspace capacity is determined by the capabilities of CNS/ATM, which includes the ground based systems and airborne systems, according to the airspace being considered.

CNS stands for:

- Communication
- Navigation
- Surveillance

Communication

The communication is built between

- ATC
- Flight to f light (Not usual)
- Flight crew
- Passenger

The communication infrastructure:

- CPDLC
- HF&VHF&Stacom
- ACARS

Navigation

Navigation is now transitioning from conventional ground-based radio navigation aids to Performance-Based Navigation (PBN). GNSS provides the solutions for both the continental and oceanic regions.

The Navigation infrastructure:

- Radio based: VOR, DME, ILS, ADF...
- Inertial based: Accelerometers, Gyroscope (Optical, MEMS, Mechanical)
- Satellite based: GPS, BEIDOU, GLONASS, GALILEO

Navigation Paremeters

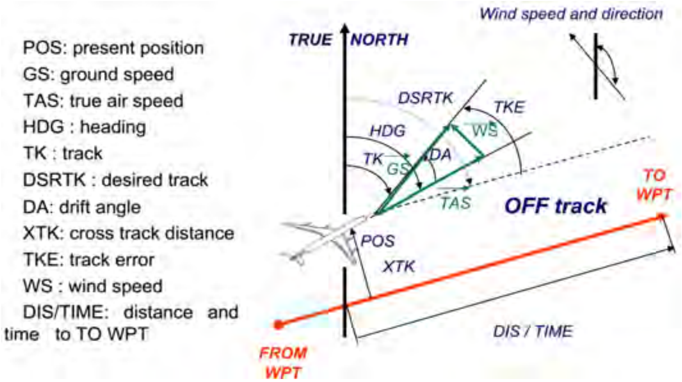


Fig. 6: Navigation paremeters (1)

Navigation Paremeters

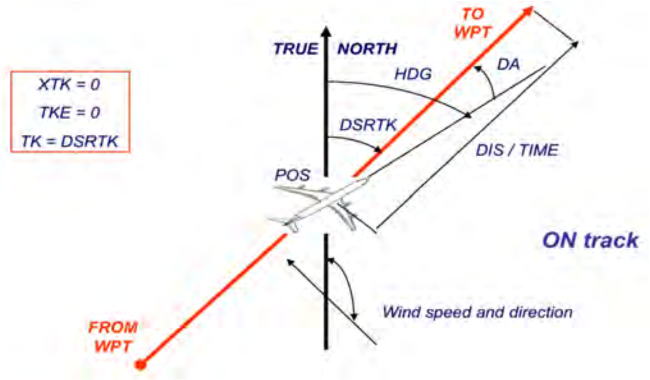


Fig. 7: Navigation parementers (2)

Navigation Paremeters Summary

	Paramètres 'air'	Paramètres inertiels	Calculs FMS(*) (*)Flight management system
Pilotage	AOA(°) β(°)	φ(°) θ(°) ψ(°)	
Guidage	ALT(ft) CAS(kts) Mach	HDG(°) TK(°) V/S[1](ft/min) FPA(°)	
Navigation (RNAV)	TAS(kts)	HDG(°) TK(°) GS(kts) WS[2] DA(°) $POS_{inertielle}$	POS[3] X-TK(NM) TKE(°) DIS(NM)

(1) Vitesse verticale baro-inertielle

(2) Intensité (kts) et direction (°) issues de la relation $\vec{WS} = \vec{GS} - \vec{TAS}$

(3) Latitude LAT (°) et longitude LONG (°) obtenues à partir de $POS_{inertielle}$ recalée à l'aide du GPS (POS GP/IRS) ou de NAVAIDS (DME-DME, VOR-DME)

PFD Idication

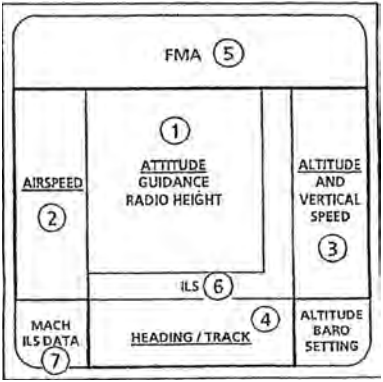


Fig. 8: PFD display

PFD Idication

Fig. 9: PFD functional area

PFD Idication

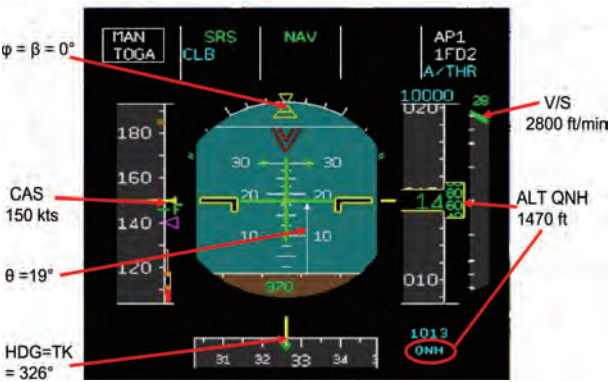


Fig. 10: PFD example

ND Idication

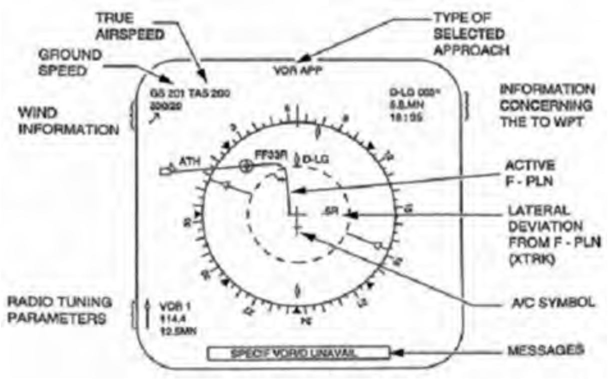


Fig. 11: ND display

ND Idication

Fig. 12: ND example

Surveillance

The surveillance system are equipped to detect the external conditions.

- Meteorology: meteorological radar
- Anti-collision:
    - Air: TCAS
    - Terrain: GPWS, eGPWS

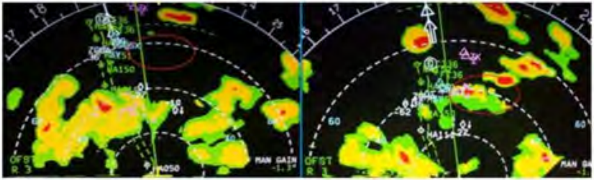


Fig. 13: Meteorological radar

Surveillance

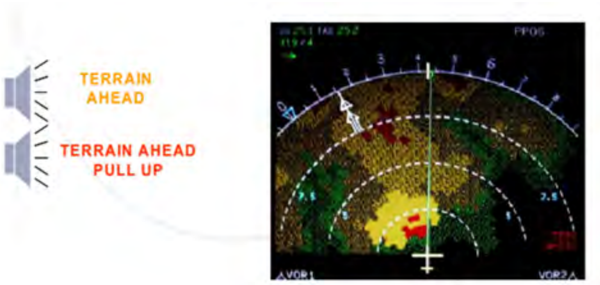


Fig. 14: TAWS

Outline

Introduction

- § Sensor definition
- § Flight control and sensors
- § The idea of CNS
- § Cockpit evolution

Air data sensors and ADC

Inertial sensors and systems

Radio navigation

GPS/GNSS

Cockpit Configuration

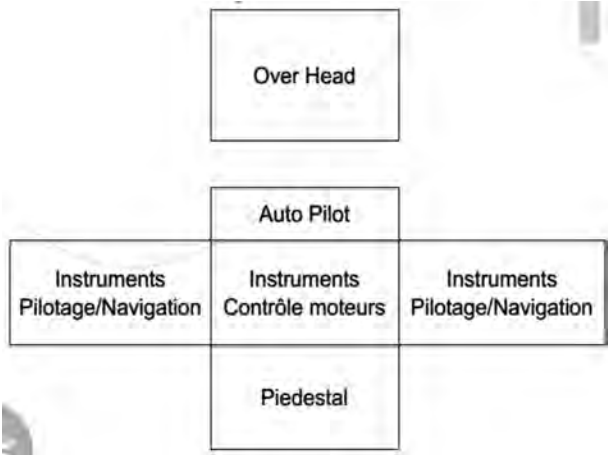


Fig. 15: Cockpit layout

Cockpit Evolution (AIRBUS)

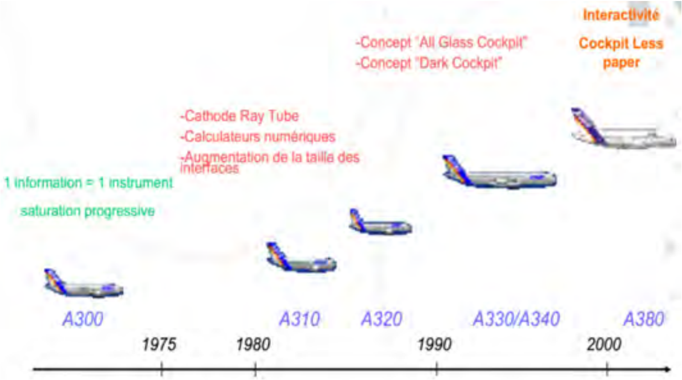


Fig. 16: Time line of AIRBUS aircrafts

Cockpit in 1920s

Single seat aircraft, the cockpit was with little standsrdization:

- Magnetic compass
- Tachometer
- Tuel gauge
- Pressure
- Clock
- Turn and slip indicator

Cockpit in 1920s

Fig. 17: Cockpit for a single seat aircraft

Cockpit in 1950s

Piston engined aircraft, "Basic Six" comes to standardized.

- Gyro artificial horizon — top center
- Airspeed — top left
- Vertical speed — top right
- Direction indicator — bottom center
- Altimeter — bottom left
- Turn and bank indicator — bottom right

Cockpit in 1950s

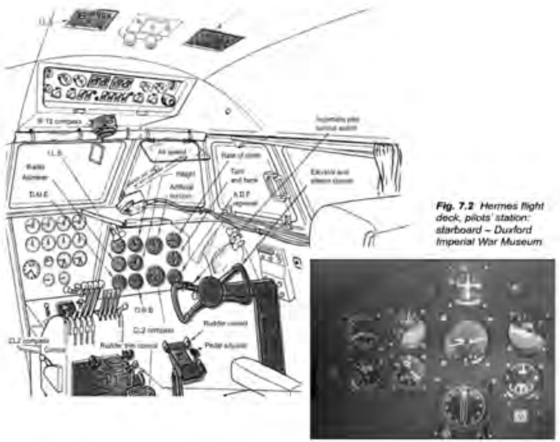


Fig. 18: Hermes's cockpit

Cockpit in 1960s

From "Basic Six" to "Basic T", still isolated, mechanical instruments. For example, mechanical pitot tube, ADI, HSI.

Fig. 19: B707's cockpit

Cockpit in 1970s

From isolated, mechnical instruments to integrated CRT instruments and "Basic T" remains the same. For example INS, EADI, EHSI.

Fig. 20: B747's CRT&mechnical instruments

Cockpit in 1980s

Concept of "Glass cockpit". For example, FMS, ADIRS, EFIS, PFD, ND.

Fig. 21: A320's LCD instruments

Cockpit in 2000s

More integrated, interactive, less paper cockpit.

Fig. 22: B787's cockpit

Outline

Introduction of Air Data

"Air Data" are the data get via the measurements of air, or atmosphere. Even air data sensors are very limited, however, through the calculation of ADC (Air Data Computer) , a lots of information concerning the flight could be provided:

- Information of the speed: IAS, CAS, EAS, TAS, Mach number
- Information of altitude: Baro altitude, V/S
- Information of attitude: AOA, AOS
- Information of environment: static temperature, pressure, air density.....

Introduction of Air Data Sensor

In modern avionics, all the calculation are performed by ADC, however, the measurements are only provided by:

- Pitot-static tube
- Total temperature sensor
- AOA sensor, AOS sensor

Air Data and Subsystems

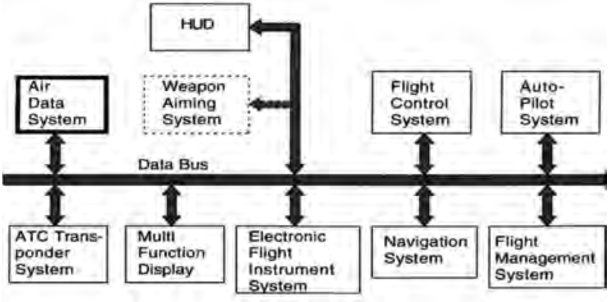


Fig. 23: Connections bewteen air data and other systems

Outline

Air Data System

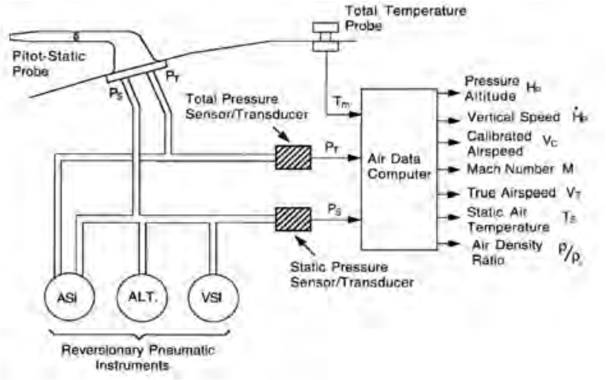


Fig. 24: Illustrations of air data system

AOA Sensor

AOA: Angle of attack for US (angle of incidence, attack angle)
Air flow sensors measures the relative motion angle between the wings (fuselage, axis of bank) and the air.

With the reading of AOA sensors, the pilot can:

- Prevent the aircraft from stall, activate stall warning/ stall protection
- Control the lift force

3 AOA sensors are equipped.

Sensor readings will be send to ADC to digitalized and corrected.

AOA Sensor

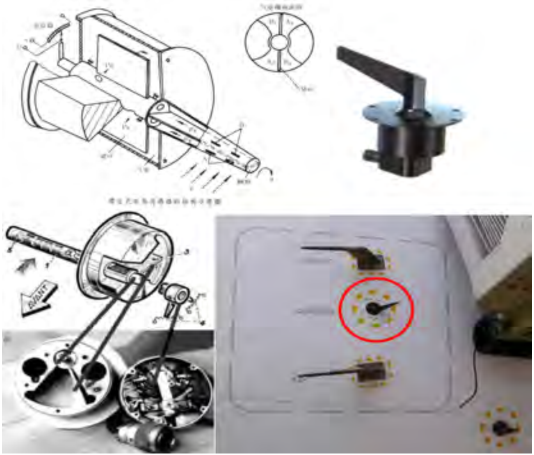


Fig. 25: AOA sensor

Pitot/Static Porbes

Pitot probe can sense the total pressure of the air, P_t.

Static pressure orifice can sense the static pressure of air, P_s.

Different types of Pitot/static probe:

- Military aircraft: combined Pitot-static tube, extends out of the aircraft.
- Civil aircraft: Pitot tube separated from static pressure orifice, allocate on the fuselage somewhere between the nose and the wing.
- In civil aircrafts, "L" type Pitot tube is very common.

The exact position of Pitot tube and static pressure orifice can only be decided by experiments and experience.

Pitot/Static Probe

Fig. 26: Pitot/static probe in civil and military aircraft

Seperated Pitot/Static Probe

Seperated Pitot/static probe is used by Airbus and Boeing, B737NG.

It will simplified the design of pitot tube and make it much easier to find the optimal position on the fuselage to place the static pressure orifice.

Combined Pitot-static tube

Combined Pitot-static tube can measure the total pressure and the static pressure at the same time, and it is used by B737.

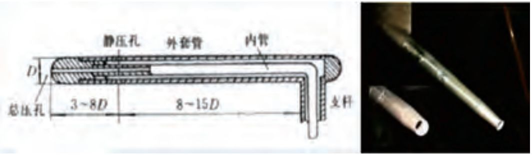


Fig. 27: Combined Pitot-static tube

Measurement Errors

Measurement errors: $P_{serror} \gg P_{terror}$

The errors may come from:

- Probe position
- Air speed
- AOA
- Some configuration of the aircraft

The errors will corrected by the ADC. The block of Pitot/static probe blockage will lead to different readings.

Vibration Lamel Sensor

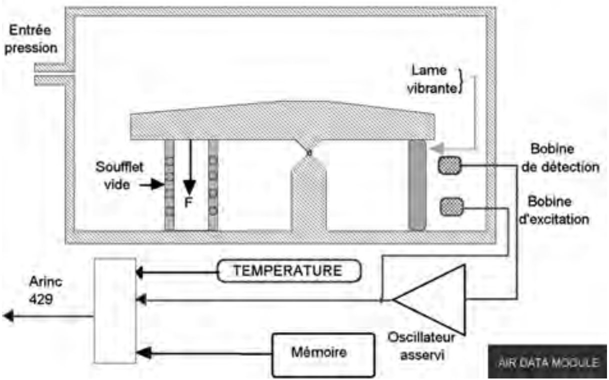


Fig. 28: Vibration lamel sensor in ADM

Temperature Sensor

Temperature measurement technology is well developed in modern industry, especially by certain temperature sensitive resistance, thermocouple, IR thermometer, etc. For the total temperature sensor,

- Sensitive elements: Platinum resistance
- Method: Callendar-Van-Dusen
- Quantity: 2 for large aircrafts

Temperature Sensor

The Callendar-Van-Dusen law,

$$\frac{R}{R_0} = 1 + \alpha \left[t_i - \delta \frac{t_i}{100} \left(\frac{t_i}{100} - 1 \right) - \beta \left(\frac{t_i}{100} \right)^3 \left(\frac{t_i}{100} - 1 \right) \right]$$

With

- t_i = temperature in °C
- R = resistance at t_i
- R_0 = resistance at 0 °C
- $\alpha = 0.003832$
- $\beta = 0.1, t \leq 0\,^\circ\mathrm{C}; \beta = 0, t \geq 0\,^\circ\mathrm{C}$
- $\delta = 1.81$

Temperature Sensor

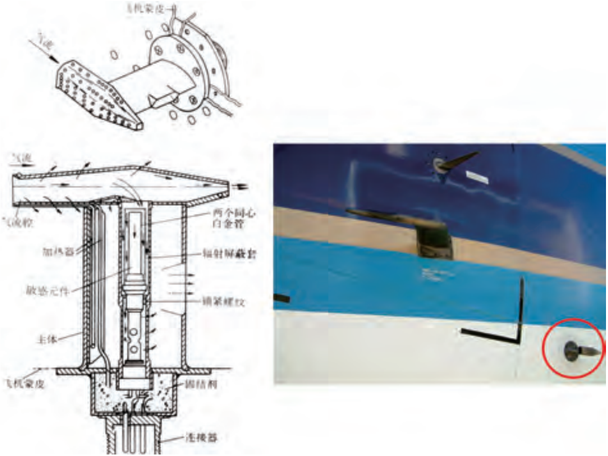


Fig. 29: Illustration of the temperature sensor

Sensor of Sideslip

The sensor of AOS are place in front of the fuselage.

The sensor structure is the same with AOA sensor.

Fig. 30: Illustration of sideslip sensor

Probe Positions

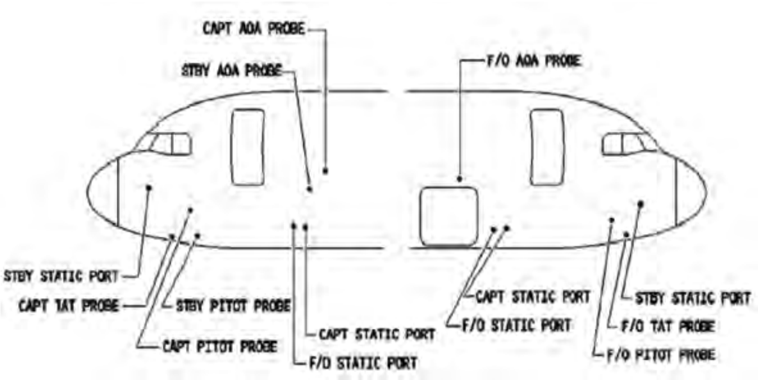


Fig. 31: Probes on the aircraft

Outline

ADC Principle

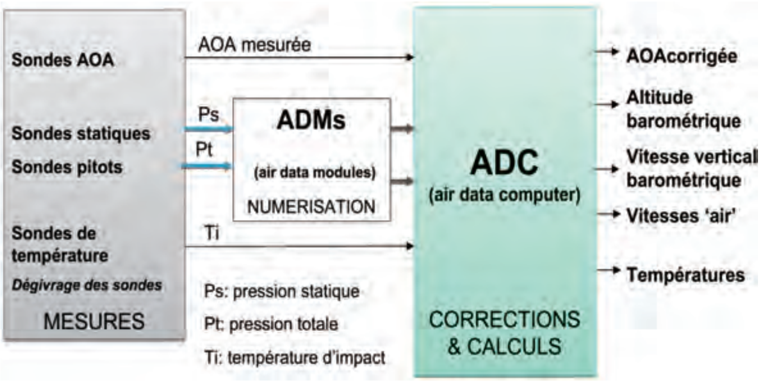


Fig. 32: ADC functional description

Corrections of AOA and Static Pressure

AOA correction:

$$AOA_{correction} = AOA_{measurement}/K + I$$

K and I can be derived by experiments, are the functions of Mach number.

P_s correction:

The error of P_s is significantly depended on Mach number, also impacted by the valve and AOA.

$$P_{scorrection} = P_{smeasurement}\left[1 + G1\left(Mach, F\right) + G2\left(Mach, AOA\right)\right]$$

$G1$ and $G2$ can be derived by experiments.

ISA

ISA: International Standard Air, issued by ISO through statistical analysis.

Standard means

- Temperature $T = 15\,^{\circ}\mathrm{C}$ (228.15 K)
- Density $\rho = 1.225\ \mathrm{kg/m^3}$
- Pressure $P = 1013.25$ hPa $= 29.92$ Hg
- Fixed temperature lapse rate:
  - Troposphere (0 km - 11 km): -6.5 °C/km (-1.98 °C/ft)
  - Stratosphere (starts from tropopause, 11 km - 20 km): -56.6 °C
  - (20 km - 32 km): +1 °C/km
  - (32 km - 47 km): +2.8 °C/km

ISA

The ISA can be classified into: Troposphere, Stratosphere, Mesosphere, Thermosphere, Outlayer.

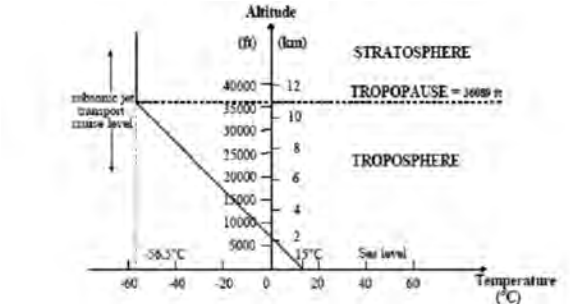


Fig. 33: Atmosphere layer

Static Pressure-Altitude Relationship

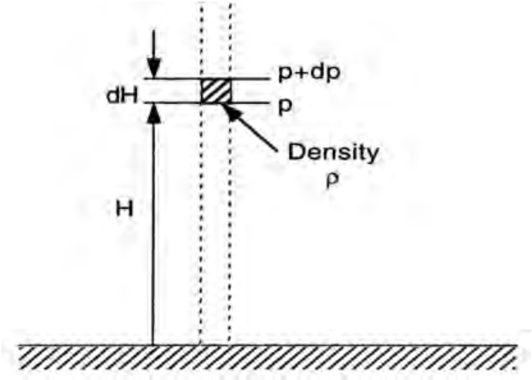


Fig. 34: Static pressure-altitude relationship

Static Pressure-Altitude Relationship (Troposphere)

From figure 34, in troposphere, we has the basic relationship

$$\mathrm{d}p = -\rho g \mathrm{d}H$$

Also with the knowledge $P = \rho RT$, $R = 287\text{J/kg}\cdot\text{K}$

In the troposphere, define,

$$T = T_b + r(H - H_b), H_b = 0,\ r = -6.5\ ^\circ\text{C/km}$$

Then

$$\frac{P}{P_0} = \left(\frac{T_b}{T_b + r(H - H_b)}\right)^{\frac{g}{rR}}, H = H_b - \frac{T_b}{r}\left(1 - \left(\frac{P}{P_b}\right)^{-\frac{Rr}{g}}\right)$$

Static Pressure-Altitude Relationship (Stratosphere)

From figure 34, in stratosphere, we have

$$\frac{1}{P}\mathrm{d}P = -\frac{g}{RT_0}\mathrm{d}h$$

After integrating, then

$$\frac{P}{P_0} = \exp\left(-\frac{g}{RT}(H - H_b)\right)$$

$$H = H_b + \frac{R}{g}T_b \ln\frac{P_b}{P}, r = 0$$

In both troposhere and straosphere, the changing of gravitational acceleration g will not be considered.

Static Pressure-Altitude Relationship

ALTITUDE (Feet)	TEMP. (°C)	PRESSURE			PRESSURE RATIO δ = P/Po	DENSITY σ = ρ/ρo	Speed of sound (kt)	ALTITUDE (meters)
		hPa	PSI	In.Hg				
40 000	-56.5	188	2.72	5.54	0.1851	0.2462	573	12 192
39 000	-56.5	197	2.58	5.81	0.1942	0.2583	573	11 887
38 000	-56.5	206	2.99	6.10	0.2038	0.2710	573	11 582
37 000	-56.5	217	3.14	6.40	0.2138	0.2844	573	11 278
36 000	-56.3	227	3.30	6.71	0.2243	0.2981	573	10 973
35 000	-54.3	238	3.46	7.04	0.2353	0.3099	576	10 668
34 000	-52.4	250	3.63	7.38	0.2467	0.3220	579	10 363
33 000	-50.4	262	3.80	7.74	0.2586	0.3345	581	10 058
32 000	-48.4	274	3.98	8.11	0.2709	0.3473	584	9 754
31 000	-46.4	287	4.17	8.49	0.2837	0.3605	586	9 449
30 000	-44.4	301	4.36	8.89	0.2970	0.3741	589	9 144
29 000	-42.5	315	4.57	9.30	0.3107	0.3881	591	8 839
28 000	-40.5	329	4.78	9.73	0.3250	0.4025	594	8 534
27 000	-38.5	344	4.99	10.17	0.3398	0.4173	597	8 230
26 000	-36.5	360	5.22	10.63	0.3552	0.4325	599	7 925

ISA Errors

IA represents the altitude errors between the ISA statistical value and the realistic situation at certain altitude, which is always nonlinear. And the IA value is also be affected by the weather conditions, especially temperature.

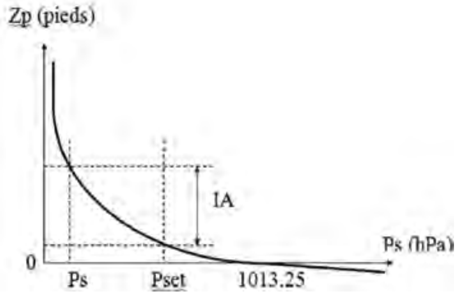


Fig. 35: ISA errors

Altitude Classification

- Absolute altitude
- Relative altitude
- True altitude
- Pressure altitude (Baro altitude)
- Elevation

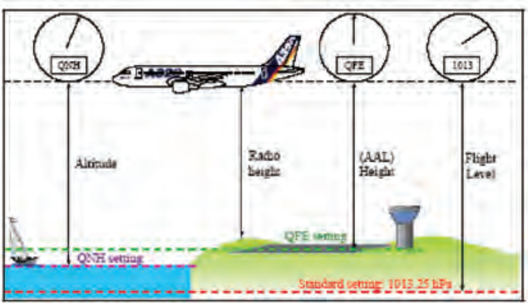


Fig. 36: Baro settings

Baro Settings

QNE,STD,1013.25:

- Reference:1013.25 hPa
- Flight Level (FL)

QNH:

- Reference: Mean Sea Level (MSL)
- Climbing, approaching.

QFE:

- Reference: airport
- Indicated altitude on the airport: zero

V/S

V/S stands for vertical speed, or rate of climbing/descent.

From the knowledge $\mathrm{d}P = -\rho g \mathrm{d}h$ and $P = \rho RT$ (Gas law)

We have:

$$\dot{H} = -\frac{RT}{P_s g}\dot{P}_s$$

Note $\dot{H}$ is the function of T and $\dot{P}_s$, and the variations of T will cause errors.

Airspeed

All the measurements for airspeed calculation are collected by Pitot/static probe, including: IAS, CAS, EAS, TAS, V/S.

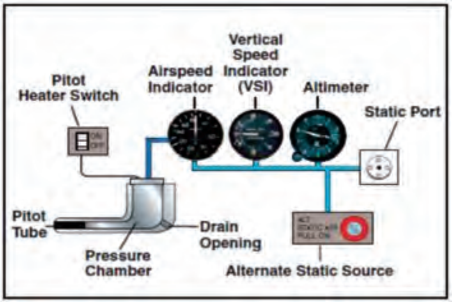


Fig. 37: Pitot/static probe

Bernouilli's and Barré Saint Venant's Relationship

IAS: Indicated air speed.

The figure below describes a sort of typical airflow, which could be described by Bernouilli relationship for ISA calculation.

We conclude,

$$\rho V \mathrm{d}V = -\mathrm{d}P \tag{1}$$

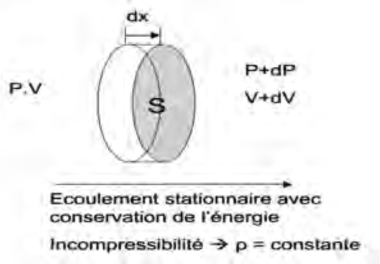


Fig. 38: Airflow with energy conservation

Bernouilli's and Barré Saint Venant's Relationship

Note equation (1) is only valid for $M_a < 0.3$, where air is incompressible, and density is constant.

With mass conservation, we have,

$$-\rho \mathrm{d}V = V \mathrm{d}\rho \tag{2}$$

By integrating equation (1), we have the above momentum equation into Bernouilli's relationship,

$$\boxed{P + \frac{1}{2}\rho V^2 = Constant}$$

Bernouilli & Barré Saint Venant's Relationship

When $0.3 \leq M_a < 1$, say, adiabatic, means air is compressible and due to the high impact pressure, density is no more constant.

The relationship between pressure and density is $P = C\rho^{\gamma}$, with $\gamma = 1.4$, C is constant.

Substituting ρ into equation (1),

$$P^{-\frac{1}{\gamma}}\mathrm{d}P + \left(\frac{1}{C}\right)^{\frac{1}{\gamma}} V\mathrm{d}V = 0 \tag{3}$$

After integration, Barré Saint Venant's Relationship is derived,

$$\boxed{\frac{\gamma}{\gamma - 1} \cdot \frac{P}{\rho} + \frac{1}{2}V^2 = Constant}$$

Speed of Sound

From $-V\mathrm{d}\rho = \rho \mathrm{d}V$ and $\mathrm{d}P + \rho V \mathrm{d}V = 0$, we have,

$$\mathrm{d}P = V^2 \mathrm{d}\rho.$$

From $P = \rho^\gamma C$, we have,

$$\mathrm{d}P = \gamma \rho^{\gamma - 1} C \mathrm{d}\rho$$

Divide the above two equations, and substituted gas law,then we derive,

$$V = \sqrt{\gamma R T} = a$$

Where a is the speed of sound. Note here γ and R are constant, means the speed of sound is decided and **only decided** by the temperature.

Mach Number

Mach number is defined by $M_a = \dfrac{V}{a}$, and could be used for:

- Control the aircraft
- Calculate the TAS
- Limitation MMO

By integrating equation (3) between the following limitations,

$$\int_{P_s}^{P_t} P^{-\frac{1}{\gamma}} \mathrm{d}P + \int_{V}^{0} \left(\frac{1}{C}\right)^{\frac{1}{\gamma}} V \mathrm{d}V = 0$$

The Mach number can be expressed through,

$$M_a = \sqrt{5\left[\left(\frac{P_t - P_s}{P_s} + 1\right)^{\frac{2}{7}} - 1\right]}$$

IAS

IAS: Indicated Air Speed.

By integrating equation (1), we have,

$$P + \frac{1}{2}\rho v^2 = Constant$$

- P —— P_s, static pressure
- $\frac{1}{2}\rho V^2$ —— P_t, impact pressure
- $Constant$ —— Total pressure

IAS is then,

$$IAS = \sqrt{\frac{2\left(P_t - P_s\right)}{\rho_0}}$$

IAS can be calculated directly by the traditional Pitot/static system and displayed by ASI (Air Speed Indicator).

CAS

CAS: Calibrated Air Speed.

By integrating equation (3) with $a_0 = 661.5$ knots $= 340.3$ m/s, $\rho = 1.225\ \mathrm{kg/m^3}$

we have:

$$CAS = a_0 \sqrt{5\left(\frac{P_t - P_s}{P_{s0}} + 1\right)^{\frac{2}{7}} - 1}$$

CAS is the function of impact pressure.

TAS

TAS: True Air Speed.

With the knowledge of $V = M_a \cdot A$ and $a = \sqrt{rRT}$, we have

$$
\begin{aligned}
V &= M_a \sqrt{rRT} \\
&= 39 M_a \sqrt{T} \text{ knots} \\
&= 20.0468\ M_a \sqrt{T} \text{ m/s}
\end{aligned}
$$

Groundspeed = TAS + Windspeed

VMO and MMO

MMO: The maximum operational Mach number that can not be exceed. For certain type of aircraft, its MMO is fixed. The value of MMO is determined by experiments.

VMO: When FL $<$ FL$_c$, the maximum operational velocity that can not be exceed, and it is related to the structure payload.

The payload is

$$F = \frac{1}{2} EAS^2 \cdot S \cdot C$$

Where EAS is Equivalent Air Speed.

The relationship between EAS, CAS and TAS are

$$EAS = \sqrt{\frac{4 + {M_{a0}}^2}{4 + M_a^2}} CAS, TAS = \sqrt{\frac{\rho_0}{\rho}} EAS$$

Static Air Temperature and Air Density Ratio

Total temperature is the impact temperature after correction by ADC.

The Static Air Temperature is given through

$$TAT = SAT(1 + 0.2k_r M_a{}^2)$$

k_r is the recovery coefficient.

Air density ratio can be expressed by

$$\frac{\rho}{\rho_0} = \frac{P_s}{P_{s0}} \cdot \frac{T_0 \left(1 + k_r 0.2 M_a{}^2\right)}{TAT}$$

Air Data on PFD and ND

Fig. 39: Air data on PFD and ND

Outline

Introduction

Gyroscopes are extremely important equipments for **navigation** transportation, which can be used to measure physical quantities through inertial law,

- Rotation angle (Free gyro,3-D gyro)
- Rotation rate (Rate gyro,2-D gyro)

The gyro-based instruments are listed,

- Attitude indicator
- Gyro compass
- Turn indicatior
- AHRS
- IMU
- ...

Construction

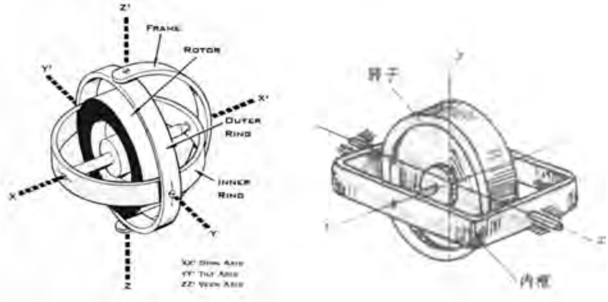


Fig. 40: 3-D gyro and 2-D gyro

Property of 3-D Gyro

3-D gyro has three typical properties:

- Rigidity: The axis of rotation (spin axis) of the gyro wheel tends to remain in a fixed direction in space if no force is applied to it.
- Nutation: A rocking, swaying, or nodding motion in the rotational axis of a gyro due to an instantaneous torque.
- Procession: The axis of rotation has a tendency to turn to the direction of an applied torque along the shortest path.

Effects on stability,

- Rotation rate of the rotor
- Moment of inertia
- The applied torque

3-d Gyro Procession

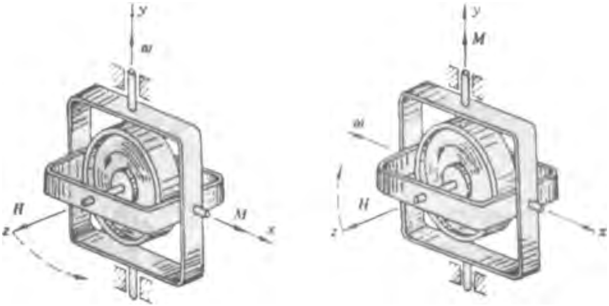


Fig. 41: Procession direction

3-d Gyro Procession Explanation

Explanation 1:

The applied torque M is the same with the movement of the end of the vector H, where H is the angular momentum of the spinning rotor.

$$\dot{\mathbf{H}} = \mathbf{v} = \mathbf{M}$$

Where v presents the motion of H.

M can be denoted by

$$\mathbf{M} = \boldsymbol{\omega} \times \mathbf{H}$$

3-d Gyro Procession Explanation

Explanation 2:

Coriolis acceleration, where $\mathbf{a}_{\omega v} = 2\boldsymbol{\omega} \times \mathbf{v}$.

Only the force that generates the Coriolis acceleration can apply torque on axis y,

$$M_y = \frac{1}{2}\pi R^2 h\rho R^2 \omega_x \Omega$$

3-d Gyro Procession Explanation

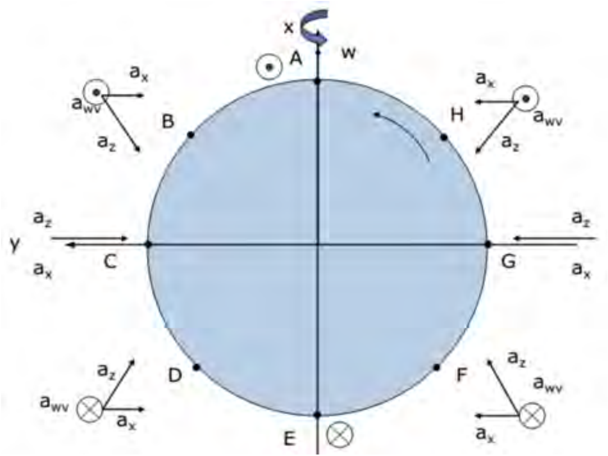


Fig. 42: Accelerations on the Rotor

3-d Gyro Procession Remarks

There are some remarks of a 3-d gyro procession,

- Procession does not happened in the direction of torque, but on the direction orthogonal to the torque.
- The procession angular rate is decided by **M**, **H** and the angle between them.
- When the torque disappeared, procession will stop immediately.
- The relationship between stability and precession.

Gyroscopic Torque

The gyroscopic torque **L** balances the applied torque **M**, and can be derived through

$$\mathbf{L} = \mathbf{H} \times \boldsymbol{\omega}$$

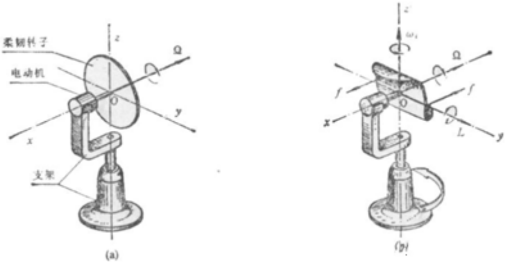


Fig. 43: Proof of gyroscopic torque

2-d Gyro Procession

The axis of the rotation has a tendency to turn to the direction of the system rotation angular velocity in the shortest path.

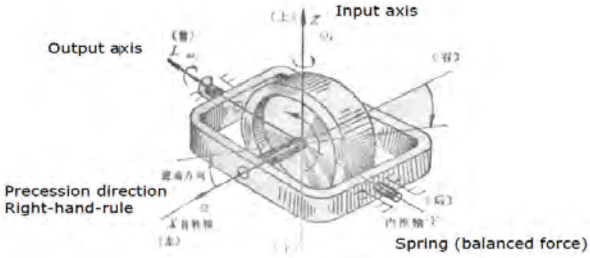


Fig. 44: Procession of 2-d gyro

Attitude Indicator

With a free gyro (Vertical gyro) (Modern gyro compatible), the attitude indicator create an artificial horizon to measure the roll and pitch. And with a gravity pendulum, the apparent motion is corrected.

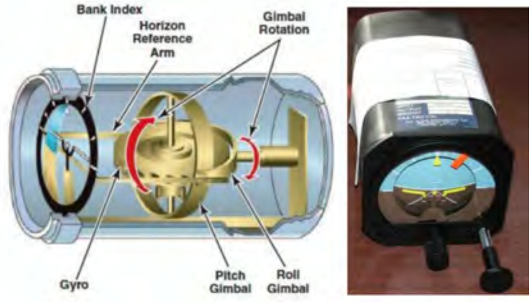


Fig. 45: Attitude indicator with a free gyro inside

Turn Indicator

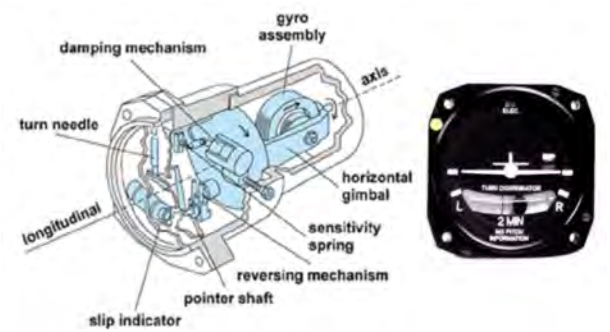


Fig. 46: Turn indicator with a rate gyro inside

Directional Gyro and Gyrocompass

- Directional gyro: Sense the direction, need correction (or aid), simple structure
- Gyrocompass: Sense north, without correction(compare to DG), complex on design

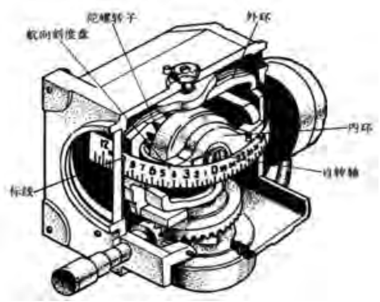


Fig. 47: Illustration of a directional gyro

Other Gyros

The research interesting in the times of mechanical gyro times, is to decrease the impact of the precession (drift). Some new gyros are invented such us gas-bearing gyroscope, electrostatically supported gyro, float integrating gyro, etc

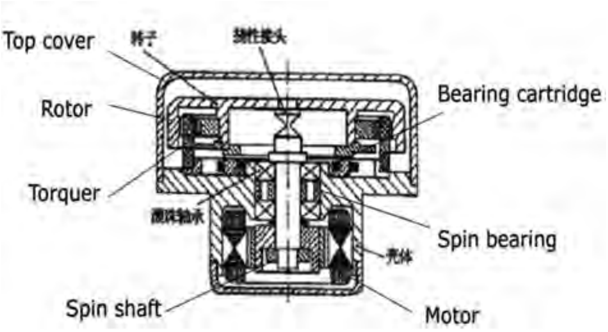


Fig. 48: The cross section view of a flexure gyro

Outline

- Sensor
- Air data sensors and ADC
- Inertial sensors and systems
  - § Conventional Gyros and Applications
  - § Modern gyros
  - § Accelerometers
  - § Inertial reference system
- Radio navigation
- GPS/GNSS

Introduction of Optical Gyro

Optical gyro is well equipped in large aircrafts,

- Sagnac Effect principle
- Classified into RLG and FOG
- Good qualities compare to the conventional gyro
  - Mechanism complexity
  - Maintenance cost
  - Warm up time
  - Shock
  - Precision
  - Lift time
  - ...

Sagnac Effect

Sagnac Effect —— to measure the optical difference.

The root of the optical gyro can be found in the experimental methodology and techniques used by Michelson and Morely (Ether drag).

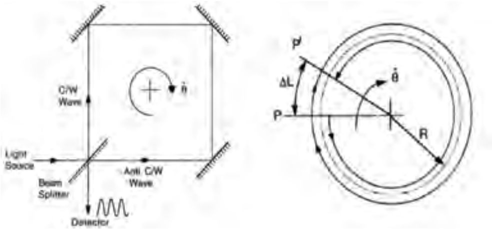


Fig. 49: Demonstration on Sagnac Effect

Sagnac Effect

The time difference in the transition time is

$$\Delta T = \frac{4\pi R^2}{c^2} \cdot \theta, \quad \Delta L = \frac{4\pi R^2}{c} \cdot \theta$$

- Hard to measure: Sagnac Effect is very small
- Realization: Relative frequency change measurements

Laser Ring Gyro (LRG)

Some improvements:

- Closed path to optical resonate cavity
- OPD measurements to frequency difference measurements

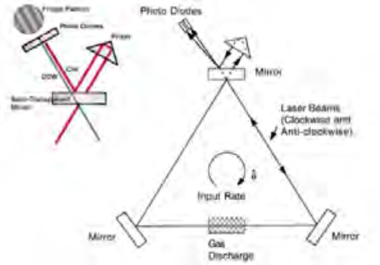


Fig. 50: Laser gyro schematic

Freq. Change Measurement

Suppose the frequency of CW and the CCW are v_1 and v_2, where $v_1 = q\frac{c}{L_1}$ and $v_2 = q\frac{c}{L_2}$

And the freq. change is then

$$\Delta v \approx \frac{\Delta L c q}{L^2}, \;\; \Delta L = \frac{4A}{c}\Omega$$

After some arrangements,

$$\Delta v = \frac{4A}{L\lambda}\Omega$$

Where L is the length of the resonate cavity. $K = \frac{4A}{L\lambda}$ is the scale factor.

Freq. Change Measurement

The frequency change can be measured through beat frequency.

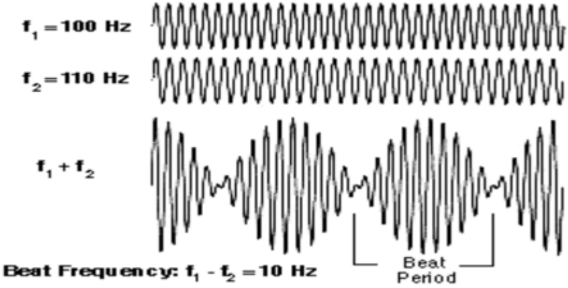


Fig. 51: Optical Beat

RLG Construction

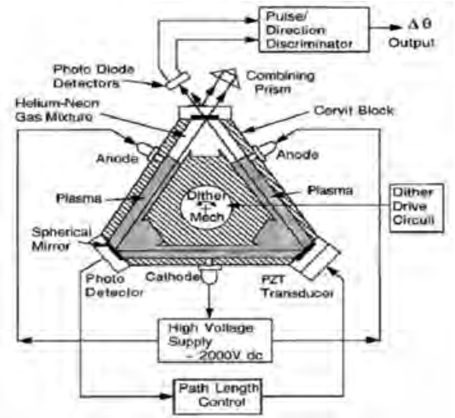


Fig. 52: Cross view of RLG

Lock in and Remedy

Lock in is the natural defects in RLG, which means at very low angular rates, RLG outputs zero.

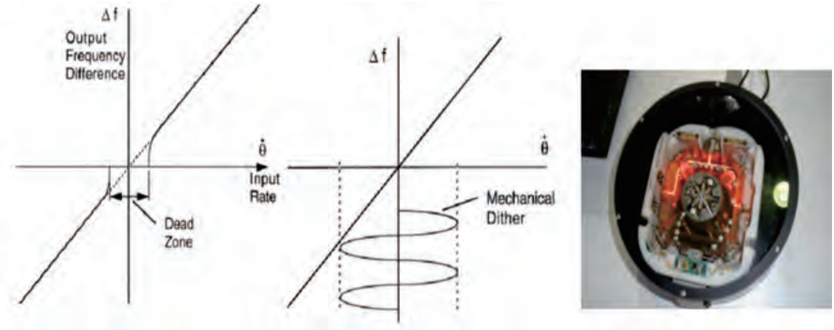


Fig. 53: Illustration of lock in and remedy

Other Considersations

The error sources in RLG, including

- Langmuir Flow Effect
  - Double anode
  - Other errors
- Scale factor error, $K = \dfrac{4A}{L\lambda}$
  - Increase $\left(\dfrac{A}{L}\right)$, while decrease λ
  - Keep the cavity highly stable in shape

Remarks on RLG

- The RLG, is inherently a linear open loop device having extremely stable input-output characteristic. It therefor dose not require any form of feedback.
- During the past decades, RLG has proven itself as the best technology in terms of performance and reliability.
- The RLG has the important advantage that the warm up time is practically zero, after powering up, it is instantly ready for operation. And the RLG hardly require recalibration. After one calibration, it maintain operational for thousands of hours.

Remarks on RLG

- The RLG is still a bulky component, typically $18cm \times 18cm \times 5cm$.
- To read from RGL, a digital counter and a navigation computer must be needed.
- Compared to the electromechanical gyros, the RLG is free of a host of inevitable error source, such as mass unbalance, residual friction torques, offsets.
- Future, the most serious contender of RLG is IFOG.

Fiber Optical Gyro (FOG)

Unlike RLG, FOG can directly measure the phase shift,

- Priciple: directly use Sagnac Effect
- Construction: multiturn optical coil fiber, Interferometric Fiber Optical Gyro (IFOG)

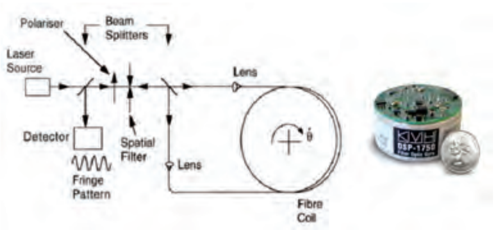


Fig. 54: Illustration of FOG

Phase Measurement

From the previous sections, we have $\Delta t = \frac{LD}{c^2}\Omega$, where L is the length of the optical fiber, D is the diameter of the coil.

And the phase shift can be calculate in the following way,

$$\Phi = \frac{2\pi LD}{c\lambda}\Omega$$

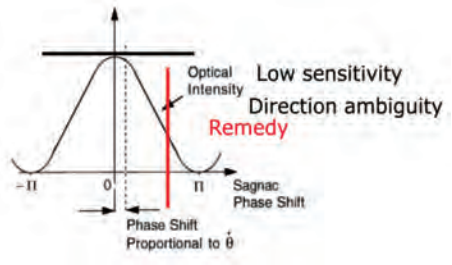


Fig. 55: Phase offset

IFOG Types

IFOG has two types,

- Open loop configuration
- Close loop configuration

Nonreciprocal and reciprocal is the key for a high precision IFOG.

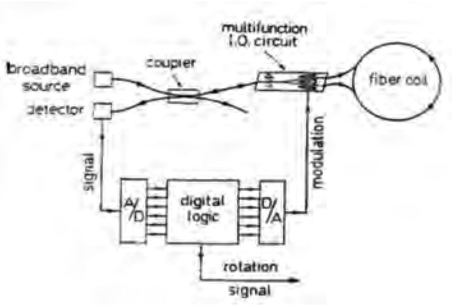


Fig. 56: FOG in close loop configuration

Error Source

- Light source noise
- Detection circuit nosie
- Fiber coil noise
  - Backscatter
  - Optical Kerr Effect
  - Briefringence
  - Faraday Effect
  - Thermal effect
- Optical elements noise
- Other noise

IFOG vs RLG

		
Size	Small	Bulky
Cost	Relatively low	High
Voltage	Low	High
Performance	high	high
Solid state	Pure	Need dither part
Sensitivity	High	High
thermal stability	Low	High

Applications of IFOG

零漂稳定度/ ((°)·h^{-1})	应用领域
>10	陆地交通工具导航、机器人姿态控制、照相机或天线稳定装置
1~10	战术导弹制导、无人驾驶飞机
0.1~1.0	航空姿态、导航参考系统(AHRS)、卫星姿态测量
0.01~0.10	航空器导航、地球测量、卫星定位
0.001~0.010	航空航天惯导系统、惯性测量陀螺罗盘、航海导航
<0.0010	精密航天器应用、精密瞄准与跟踪

MEMS Gyro

MEMS: Micro Electro-Mechanical System

Drawbacks and the needs for MEMS gyro:

- Size and Cost
- Operational Cost
- Challenges for fabrication process
- Test, measurement and calibration

Development Trajectory

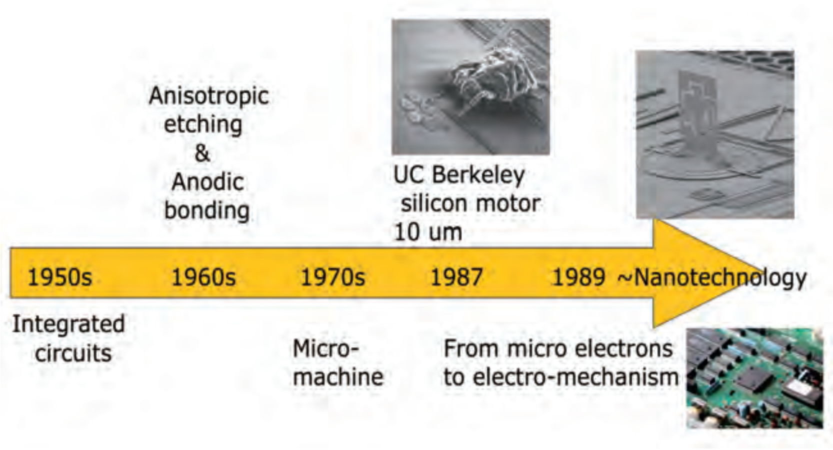


Fig. 57: Development of MEMS technology

Advantages

Compared to mechanical and optical gyros,

- Small size, low cost and low power
- Almost no maintenance cost
- Shock survival
- High reliability

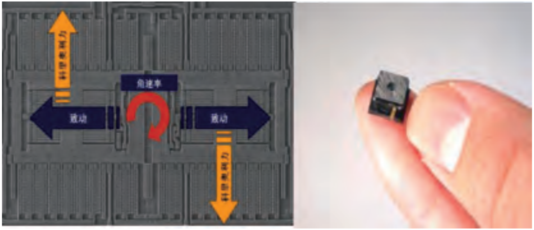


Fig. 58: Examples of MEMS gyro

Principle

Unlike Mechanical and optical gyros, the basic principle of MEMS gyros lies in Coriolis Effect.

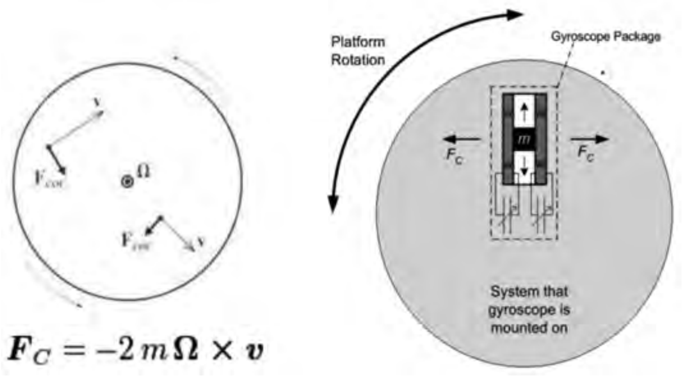


Fig. 59: Coriolis Effects

Two More Examples

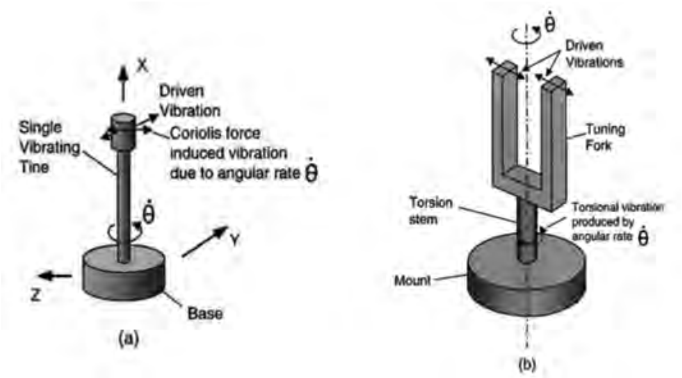


Fig. 60: Tuning fork rate gyro

AHRS

AHRS: Attitude Heading Reference System. Equipped on the aircrafts which do not have INS and IRS.

Support by the modern technologies,

- Mostly MEMS sensors based
- Can be configured into IMU, AHRS, NAV unit...
- 3 gyros (1 DG, 1 VG), 3 accelerators, 3 magnetometers
- Strip down strcuture
- 2 phases to operate
- Within horizonal plan and magnetic north
- Kalman Filter, low pass filters corrections

AHRS440

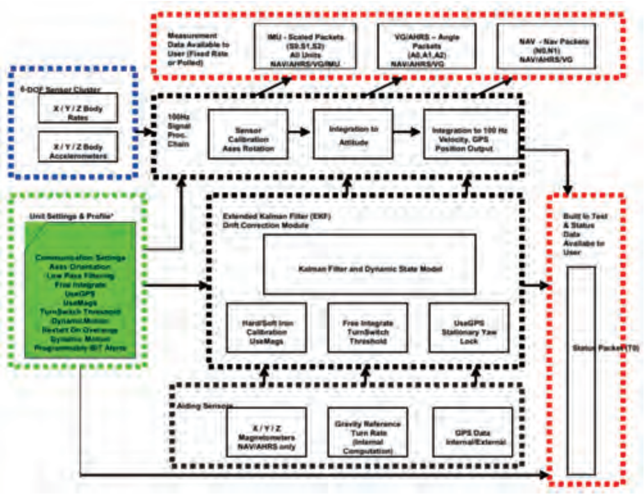


Fig. 61: Software diagram in blocks

AHRS440

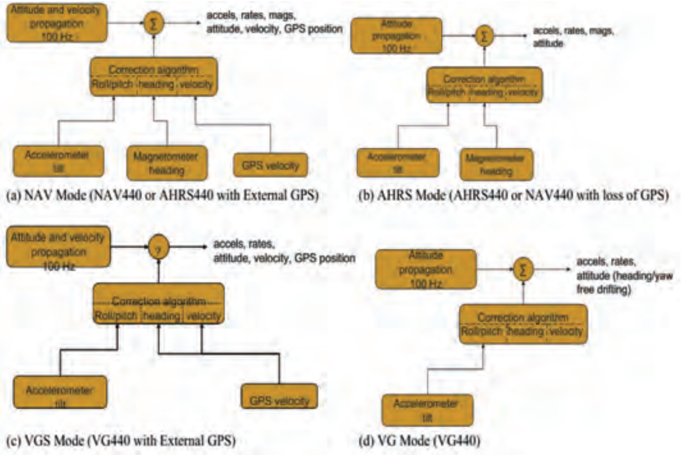


Fig. 62: Functional block diagram of NAV, AHRS and DV in default mode

Outline

- Sensor
- Air data sensors and ADC
- Inertial sensors and systems
  - § Conventional Gyros and Applications
  - § Modern gyros
  - § Accelerometers
  - § Inertial reference system
- Radio navigation
- GPS/GNSS

Principle

Unlike gyros, the accelerometers mostly based on Newton's Second Law. Certain mass is employed as the sensitive elements.

The accelerometer has suffered the following errors,

- Bias drift
- Misalignment
- G-sensitivity
- Nonlinearity
- Scale factor error
- ...

Principle

Accelerometer is used to measure **Specific Force** f, which is non-gravitational force.To measure the actual acceleration, the output of an accelerometer can not be used directly. The specific force equation is,

$$\dot{\mathbf{V}}_{eT}^{T} = \mathbf{f}^{T} - \left(2\omega_{ie}^{T} + \omega_{eT}^{T}\right) \times \mathbf{V}_{eT}^{T} + \mathbf{g}^{T}$$

Where

- $\mathbf{V}$: The velocity of certain frame relative to earth frame.
- $\mathbf{f}$: Accelerometer output.
- $\boldsymbol{\omega}_{\mathbf{ie}}$ and $\boldsymbol{\omega}_{\mathbf{eT}}$: The angular rate of earth frame relative to inertial frame, the angular rate of certain frame relative to earth frame.
- $\mathbf{g}$: Gravitational acceleration

Example

For inertial navigation, the sensitivity will be better than $10^{-4}g$.

In modern aviation, the accelerometers are,

- Liquid floated pendulous accelerometer
- Quartz flexure pendulum accelerometer
- MEMS
- ...

Liquid Floated Pendulous Accelerometer

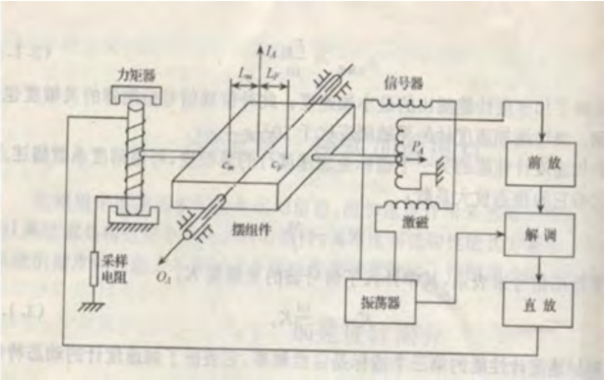


Fig. 63: Functional diagram of the LFPA

Other Examples

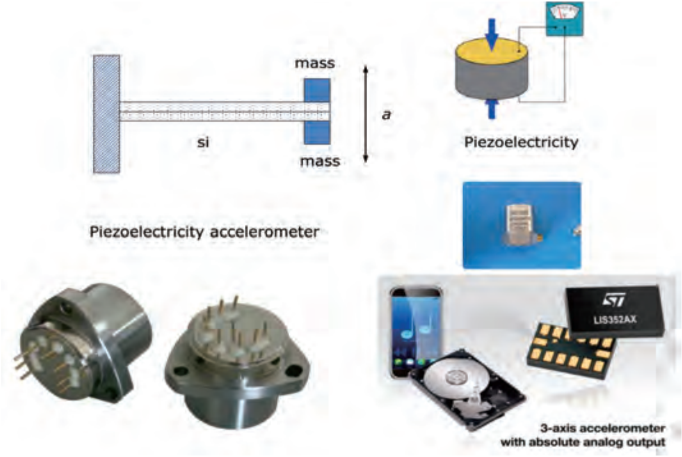


Fig. 64: Other examples of accelerometers

Applications

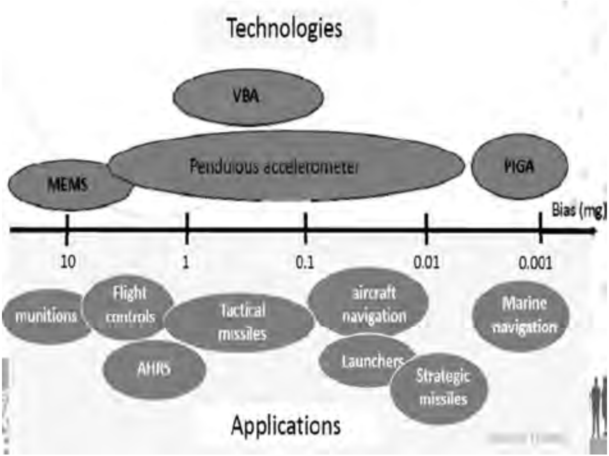


Fig. 65: Applications of accelerometers in different grades

Outline

- Sensor
- Air data sensors and ADC
- Inertial sensors and systems
  - § Conventional Gyros and Applications
  - § Modern gyros
  - § Accelerometers
  - § Inertial reference system
- Radio navigation
- GPS/GNSS

History

INS: Inertial Navigation System

- Motion sensors (accelerometers)
- Angular sensors (1\2\3, gyroscopes, optional)
- Gimballed platforms (gyrostabilized and fluid-suspended gyrostabilized)
- Stabilization control
- Correction control
- Schüler Tuning

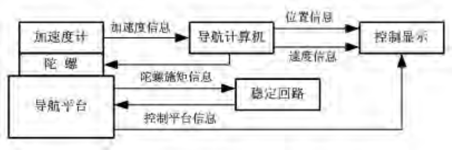


Fig. 66: Principle of INS

IRS

IRS: Inertial Reference System (Strap down navigation)

- Motion sensors(accelerometers)
- Angular sensors(3 rate gyroscopes)
- Digital computer to replace gambled platform

IRS vs INS

Now IRS is commonly used in commercial and tactical applications.

- Reduced construction complexity
- No more gamble lock
- Sensors directly attached to the vehicle
- Dynamic range in several thousands Hz, whereas INS in 50-60 Hz
- Less operation cost
- Less structure defects (Mass unbalance, etc), more reliable
- RLG to replace conventional gyros
- Less difficulties in manufacture and cost reduction
- Easy for sensor fusion

Alignment

Alignment: to find the orientation and attitude by inertial sensors. Alignment is the first step after the startup of the IRS, usually when the aircraft is on the apron.

- Two steps: coarse alignment and refined alignment.
- Sensors: accelerometer and gyro.
- Frame: horizon and north (geographic frame, and to Navigation frame)
- Coarse alignment: to define the orientation (roll,pitch, yaw) and latitude.
- Refined alignment: by kalman filter to correction the errors in orientation(attitude matrix).
- Alignment initialization: the knob from "OFF" to "NAV",("ALIGN" for Boeing).
- Usually take 10 min.
- Alignment check.

Alignment

In all phases of alignment, the reference is the gravitational acceleration and the earth rotation angular rate. Coarse alignment will lasts 30 sec to determine the orientation as soon as possible.

- Accelerometer: to sense the pitch and roll by the X-Y axis output.
- Gyro: to sense the yaw and latitude by the X-Y axis output.
- The coarse alignment dose not take the external turbulence into consideration.

Refined alignment will lasts at least 9 min 30 sec to correct the errors in the attitude matrix.

During the alignment (after 5 min), the pilot need to input the latitude and longitude. Then the alignment check will initialized.

Alignment

During the alignment, the "ALIGN" in CDU may start to flash.

- IRS failure
- No latitude and longitude input within 10 min
- Big difference between the input position and the last position recorded by the aircraft

Attitude

The attitude in IRS is represent by quaternion. The differential equation of quaternion is,

$$\begin{bmatrix} \dot{q}_0 \\ \dot{q}_1 \\ \dot{q}_2 \\ \dot{q}_3 \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 0 & -\omega_x & -\omega_y & -\omega_z \\ \omega_x & 0 & \omega_z & -\omega_y \\ \omega_y & -\omega_z & 0 & \omega_x \\ \omega_z & \omega_y & -\omega_z & 0 \end{bmatrix} \begin{bmatrix} q_0 \\ q_1 \\ q_2 \\ q_3 \end{bmatrix} \tag{4}$$

Where $\omega_{nb}^b = \omega_{ib}^b - C_n^b(\omega_{ie}^n + \omega_{en}^n)$, ω_{ib}^b is the output of the RLG, C_n^b is the attitude matrix, ω_{ie}^n and ω_{en}^n is the position angular rate and earth rotation rate projected on axis X, i,n and b represent inertial frame, navigation frame and body frame.

Attitude

And $\omega_{ie}^n + \omega_{en}^n$ can be derived from,

$$\omega_{ie}^n + \omega_{en}^n = \begin{bmatrix} -\frac{V_N}{R_M} \\ \omega_{ie}\cos L + \dfrac{V_E}{R_N} \\ \omega_{ie}\sin L + \dfrac{V_E}{R_N}\tan L \end{bmatrix}$$

Where R_M and R_N is the radius of meridian and prime vertical of the earth, ω_{ie} is the earth rotation angular rate, L is the latitude, V_N and V_E are the velocity to north and east, L, V_N and V_E are keeping updating by navigation calculation.

Attitude

By updating the quaternion, the attitude matrix C_n^b,

$$C_n^b = \begin{bmatrix} T_{11} & T_{21} & T_{31} \\ T_{12} & T_{22} & T_{32} \\ T_{13} & T_{23} & T_{33} \end{bmatrix}$$
$$= \begin{bmatrix} 1-2\left(q_2^2+q_3^2\right) & 2\left(q_1q_2-q_0q_3\right) & 2\left(q_1q_3+q_0q_2\right) \\ 2\left(q_1q_2+q_0q_3\right) & 1-2\left(q_1^2+q_3^2\right) & 2\left(q_2q_3-q_0q_1\right) \\ 2\left(q_1q_3-q_0q_2\right) & 2\left(q_2q_3+q_0q_3\right) & 1-2\left(q_1^2+q_2^2\right) \end{bmatrix}$$

And the Roll $\theta = \arcsin(T_{32})$, Pitch $\gamma = \arctan\left(-\frac{T_{31}}{T_{33}}\right)$, Yaw $\psi = \arctan\left(\frac{T_{12}}{T_{22}}\right)$, note γ and ψ are four quadrant arctangent.

Naviagtion

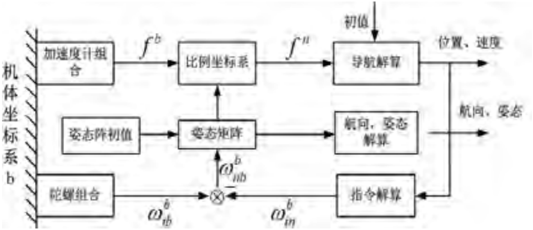


Fig. 67: Work flow of strip down inertial navigation system

Navigation

Rearrange the specific force equation into matrix,

$$\begin{bmatrix} \dot{V}^n_{enx} \\ \dot{V}^n_{eny} \\ \dot{V}^n_{enz} \end{bmatrix} = \begin{bmatrix} f^n_x \\ f^n_y \\ f^n_z \end{bmatrix} - \begin{bmatrix} 0 & -\left(2\omega^n_{iez} + \omega^n_{enz}\right) & 2\omega^n_{iez} + \omega^n_{enz} \\ 2\omega^n_{iez} + \omega^n_{enz} & 0 & -\left(2\omega^n_{iex} + \omega^n_{enx}\right) \\ -\left(2\omega^n_{iey} + \omega^n_{eny}\right) & 2\omega^n_{iez} + \omega^n_{enz} & 0 \end{bmatrix} \times \begin{bmatrix} V^n_{enz} \\ V^n_{eny} \\ V^n_{enz} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ g \end{bmatrix}$$

Navigation

Then we got,

$$\dot{L} = \frac{V_{eny}^{n}}{R_M + h}$$

$$\dot{\lambda} = \frac{V_{enx}^{n}}{(R_N + h)\cos(L)}$$

$$\dot{h} = V_{enz}^{n}$$

Note altitude h must be aided before provided to the pilot.

Hybridation

The measurements provided by IRS, will keep drifting along time.

Normally it could be aided by,

- GNSS
- Baro altitude
- Astronomical measurements
- Topographic information
- ...

ADIRS

ADIRS = Air data + IRS

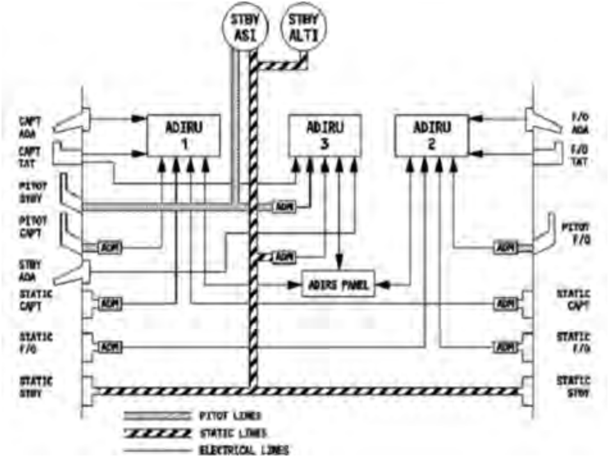


Fig. 68: ADIRS in Airbus

ADIRS

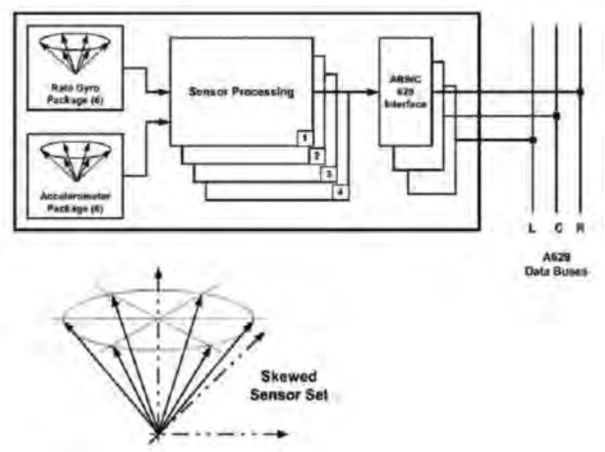


Fig. 69: ADIRU in Boeing——inertial sensor

ADIRS

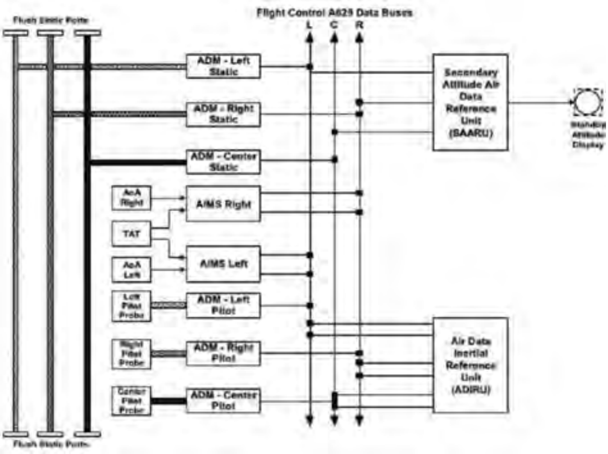


Fig. 70: ADIRU in Boeing——ADIRU structure

Control Panel

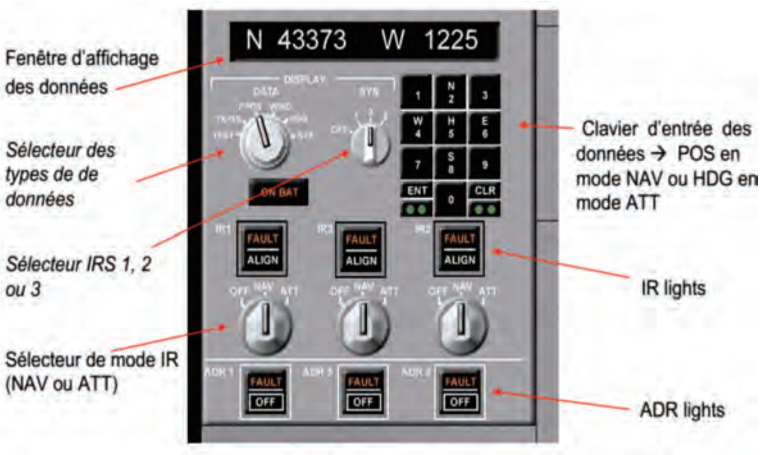


Fig. 71: ADIRS control panel in Airbus

Parameters Precision "Air Data"

Paramètre	Précision à 3σ(99.9%)[domaine opérationnel]
AOA	0,5 à 1° [- 40 à + 90°]
ALT standard	30 ft à 5000 ft/M0.3 et 70 ft à 35000 ft/M.0,78 [-2000 à+50 000 ft]
V/S	30 ft/min [-/+ 20 000 ft/min]
Mach	0,03 à M0.3 et 0.005 à M0.8 [de 0.1 à 1.0]
CAS	3,3 kts à 150 kts et 1.3 kts à 265 kts/M0.78 [de 30 à 450 kts]
TAS	3 kts [de 60 à 599 kts]
TAT	1° [de - 60 à 99°]
SAT	1° [de - 99 à + 80°]

Parameters Precision "Inertial Quantities"

Paramètre	Précision à 2σ(95%)[domaine opérationnel]
Nx_p, Ny_p, Nz_p	0,005 g [-/+ 4g]
p, q, r	0,025°/s [-/+ 128°/s]
Roulis et tangage	0,1°
HDG	0.4° + erreur de déclinaison magnétique (2 à 5°)
TK	2° + erreur de déclinaison magnétique
FPA	0.3° à GS 200 kts
GS	8 kts
Wind information	vitesse: 8 kts; direction: 10 °
LAT, LONG	dérive de $POS_{inertielle}$ de 2 NM/h

Outline

Sensor

Air data sensors and ADC

Inertial sensors and systems

Radio navigation

- VOR
- DME
- ADF
- ILS

GPS/GNSS

Principle

VOR: VHF Omnidirectional Range.

VOR provides orientation measurement (QDR) for the aircraft according to certain VOR/DME bacon.

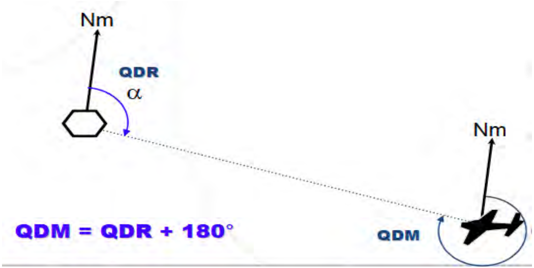


Fig. 72: QDR measurement by VOR

Principle

The basic principles for VOR,

- VOR radiates the carrier modulated by 2 30 Hz signals.
  - Reference signal, phase is identical regardless the azimuth.
  - Variable signal, phase shift is proportional to the azimuth.
- Magnetic north as the reference.
- Could be coupled with DME.
- Channels within 108-117.95 MHz.
  - 40 channels within 108-111.85 MHz if the first decimal place is even number (Otherwise LOC).
  - 120 channels within 112-117.95 MHz.
- Types: CVOR, DVOR, TVOR (Terminal VOR).
- Always be identified by 2 or 3 letters (TOU, FJR, BT. . . .)

CVOR Signal

30 REF, transmitted by omnidirectional antenna,

- Frequency modulation with 9960 Hz subcarrier.
- Amplitude modulation with VHF carrier.
- Phase are identical in all directions.

30 VAR, transmitted by directional antenna,

- Amplitude modulation with VHF carrier.
- Rotation at 30 Hz.
- Phase changes in different direction.

The errors of CVOR lies in 3°-5°.

CVOR Signal

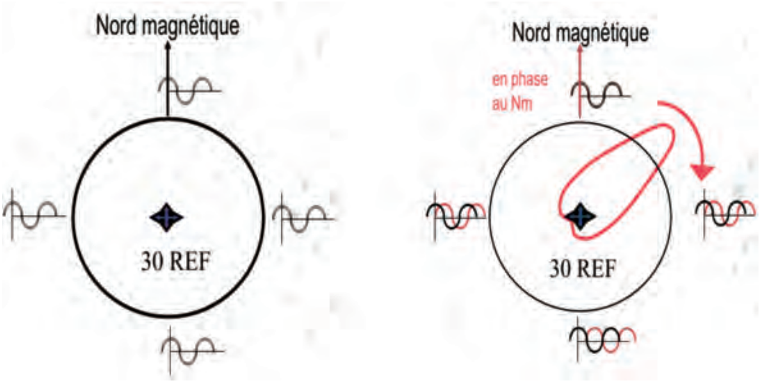


Fig. 73: 30 REF and 30 VAR

DVOR

DVOR: Doppler VOR.

- More robust and accurate than CVOR.
- Less sensitive to site error.
- 30 VAR and 30 REF are inverted. The REF is AM signal and VAR is FM.
- 48 antennas on a circle, pseudo rotation: each antenna will activated alternately.
- Pseudo rotation induced a doppler modulation of the carrier.
- The airborne equipment is compatible with CVOR and DVOR.
- The errors of DVOR lies in 1°.

CVOR and DVOR

Fig. 74: CVOR and DVOR

Airborne Equipments

The airborne equipments of VOR including a vertical antenna, NAV panel (frequency setting), receiver (display).

- Automatic chain (no pilot action, continues display)
  - RMI, Radio Magnetic Indicator
- Manual chain (the pilot need to choose a reference radial)
  - CDI, Course Deviation Indicator
  - HSI, Horizontal Situation Indicator

Fig. 75: NAV panel

RMI

Fig. 76: RMI display

CDI

OBS: Omni-bearing selector

Fig. 77: CDI display

CDI

Sector definition: from/to. VOR sector: +/- 10°. Use a radial close to your HDG, HDG-90° < OBS < HDG+90°.

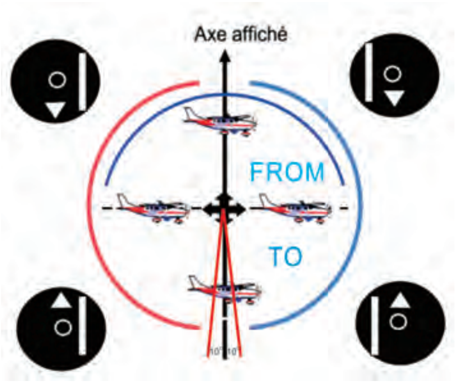


Fig. 78: From / to sector

HSI

HSI is essentially a CDI inside a compass card.

Fig. 79: HSI display

Example

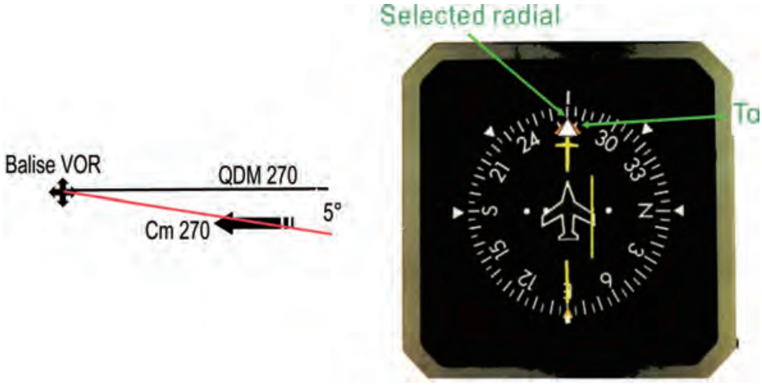


Fig. 80: HSI readings

Example

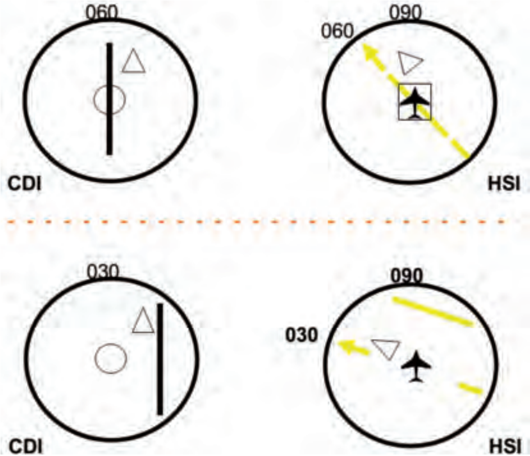


Fig. 81: HSI and CDI readings

VOR (DME) on ND

On ND, RMI can be displayed on NAV/A mode, and HSI can be displayed on VOR mode.

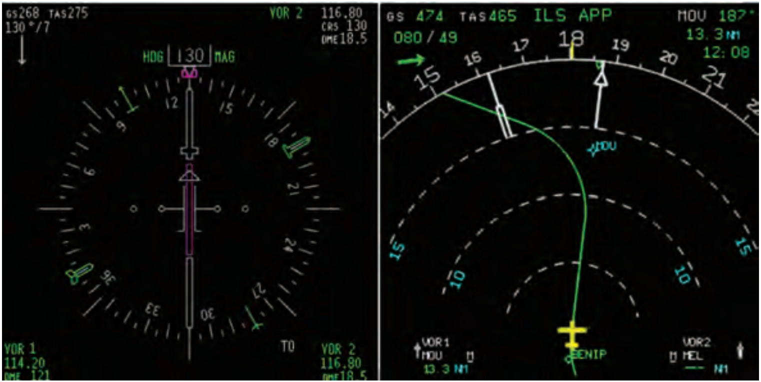


Fig. 82: ND on VOR and NAV/A mode

VOR Application

VOR could be used for positioning and navigation.

Positioning,

- VOR-VOR
- VOR-DME

Navigation,

- HSI, CDI, RMI, to follow the WPT

Outline

Sensor

Air data sensors and ADC

Inertial sensors and systems

Radio navigation

- VOR
- DME
- ADF
- ILS

GPS/GNSS

Principle

DME: Distance Measuring Machine.

- Slant range
- Two components are include
  - Aircraft component: the interrogator, 1025 MHz - 1150 MHz, Spacing 1 MHz.
  - Ground component: the transponder, 962 MHz - 1213 MHz, spacing 1 MHz, X/Y 252 channels (52 unavailable).
- UHF carrier

Principle

DME measures the propagation time on double path, when D(Nm) $>$ H(1000fts), the error will be less than 1.5%.

The slant range can be derived by,

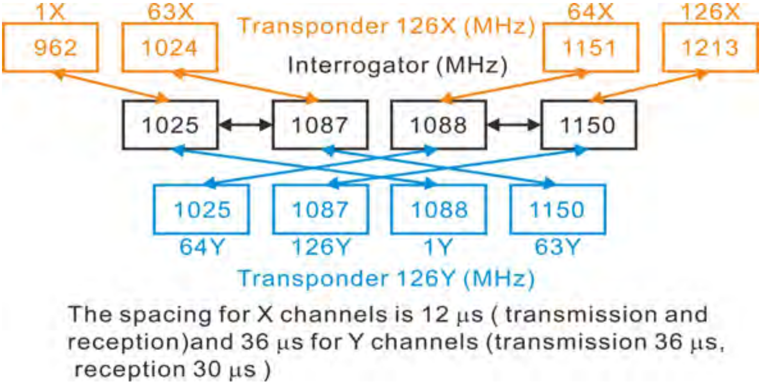
$$D(m) = 150\,(\Delta t - 50)\,\mu s$$

and

$$D(Nm) = 0.0809\,(\Delta t - 50)\,\mu s$$

Where 50 μs is the time delay inside DME station.

Frequency and Channels



Interrogation Signal

The interrogator signals: pulse pairs are transmitted on both X channels and Y channels at random intervals. On average, 150 paired pulses will be transmitted per second.

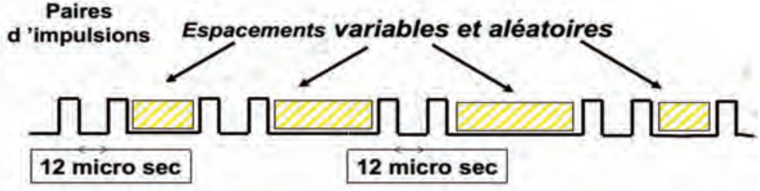


Fig. 83: Paired pulse at random intervals

Working Modes

Two working stages exist for DME,

- Search mode: to achieve a rapid lock on the DME interrogator radiates 150 pps for 100 s maximum (high bit rate). It takes 5 seconds for modern DME.
- Tracking mode: when the interrogator receive more then 50% replies, the tracking mode will start (lock on), the system operates at 25 (20-30) pps (Low bit rate).

DME Station

DME station: transponder. A DME station can handle 100 (200) aircrafts at the same time.

Two types of DME,

- DME/N
- DME/P

DME coule be co-located with,

- VOR: VOR-DME
- Glide: ILS-DME

Once the VOR/ILS frequency is set, the correspondent DME is selected.

DME Station

Fig. 84: DME with VOR and GLIDE

DME Application

DME can be used for,

- Definite the WPT with QDR/Distance
- DME wait
- DME arc
- Approcah ILS-DME, VOR-DME
- RNAV
- Positioning

Note the DME-speed and DME-arrival time is correct only when the aircraft is flying along certain QDR/QDM.

Note when the aircraft is approach DME station, the distance error will become increasing, especially when distance = altitude.

Outline

Sensor

Air data sensors and ADC

Inertial sensors and systems

Radio navigation

- VOR
- DME
- ADF
- ILS

GPS/GNSS

ADF

ADF: Auto Direction Finder.

- Work with NDB (Non-directional Beacon), or civil radio beacon.
- Measure relative bearing.
- Displayed by RBI (Relative Bearing Indicator) and RMI (Radio Magnetic Indicator).
- NDB ground station operates in 190 kHz - 1750 kHz (LF, MF).
- Accuracy $+/- 5\ ^\circ$.

ADF

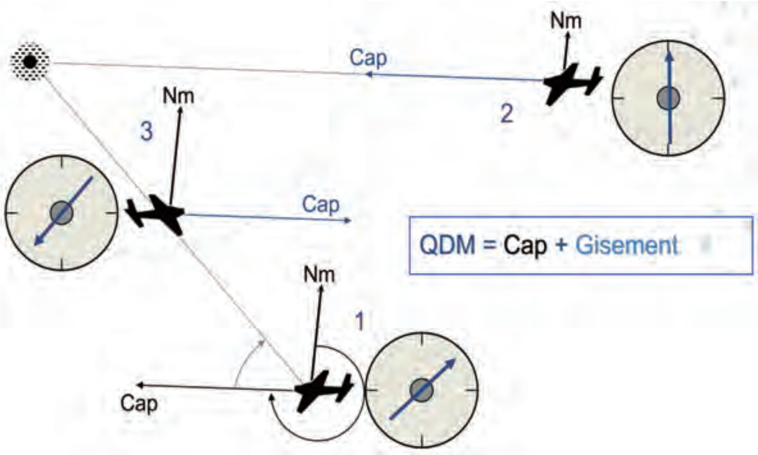


Fig. 85: Relative bearing measured by ADF

Outline

- Sensor
- Air data sensors and ADC
- Inertial sensors and systems
- Radio navigation
  - § VOR
  - § DME
  - § ADF
  - § ILS
- GPS/GNSS

ILS

ILS: Instrument Landing System. ILS is to provide pilot guidance on the glide path to the runway. With the help of the ILS's visual guidance, the pilot can fly to the DH (Decision Height).

- Precision approach guidance system, can provide guidance in both horizontal and vertical plane.
- Constructed by Localizer and Glide Path.
- LOC: 40 channels shared with VOR frequency, 108 MHz - 112 MHz (108.1 MHz, 108.15MHz, 108.30 MHz . . .)
- GP: 40 channels within UHF, 329 MHz - 335 MHz, paired with LOC.
- Displayed by CDI, HSI, PFD. . . .

ILS

Fig. 86: LOC antenna

LOC Principle

Localizer (LOC or LLZ) radiates 2 strictly synchronous VHF carriers with 2 patterns. The modulation is 150 HZ for the right pattern, and 90 Hz for the left pattern (modulation depth 20%). The receiver just sees one carrier modulated with 90 Hz and 150 Hz.

- DDM: Difference in Depth of Modulation. Runway centerline, DDM $= 0$.
- SDM: Sum in Depth of modulation. Runway centerline, SDM $= 0.4$.

DDM increases with the displacement of the centerline.

When SDM < 0.4, the warning flag will appear.

LOC Principle

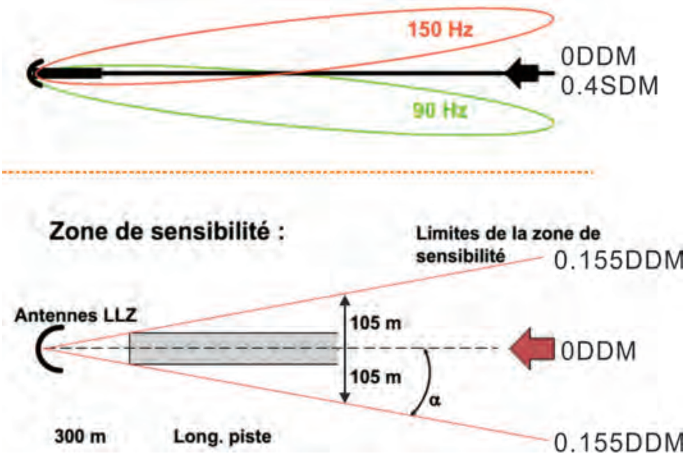


Fig. 87: LOC signal principle

LOC Trajectory

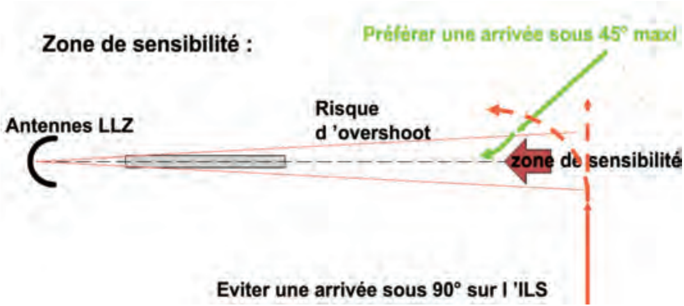


Fig. 88: LOC trajectory

Azimuth Coverage Sector

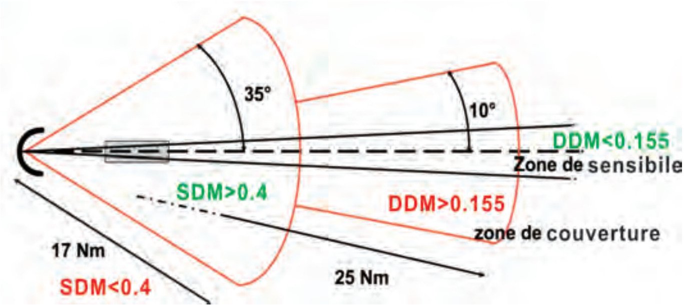


Fig. 89: LOC azimuth coverage

Vertical Coverage Sector

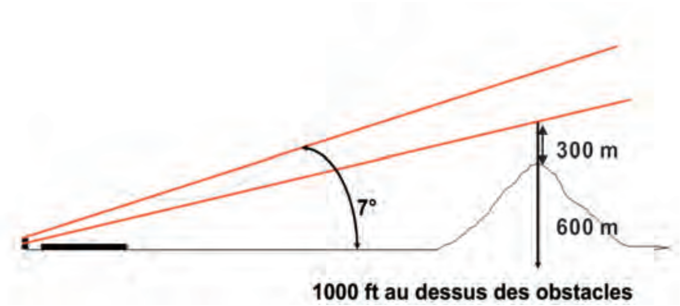


Fig. 90: LOC vertical coverage

GP Principle

GP: Glide Path. GP is employed to guide the aircraft to descend along the elevation angle of 3 $^\circ$ and 15 m above the threshold. The radio pattern is similar to the LOC, but in the vertical plane, and the azimuth angles are replaced by elevation angles.

- Operated in UHF, 329 MHz - 335 MHz, 40 channels.
- 150 Hz for the lower pattern and 90 Hz in the higher pattern (modulation depth 40%).
- DDM and SDM, DDM is proportional to the angular deviation.
- GP frequency is paired with LOC.
- GP station located 300 m from the threshold, around 150 m from the runway centerline.

GP Principle

Fig. 91: GP antenna

GP Principle

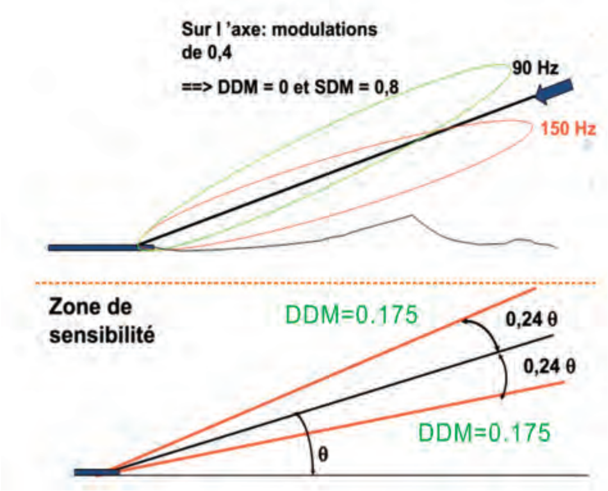


Fig. 92: GP signal principle

GP Coverage Sector

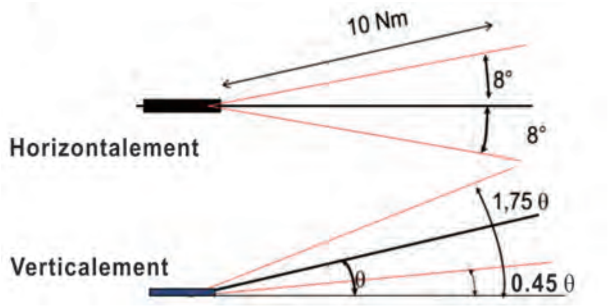


Fig. 93: GP Coverage sector

GP Trajectory

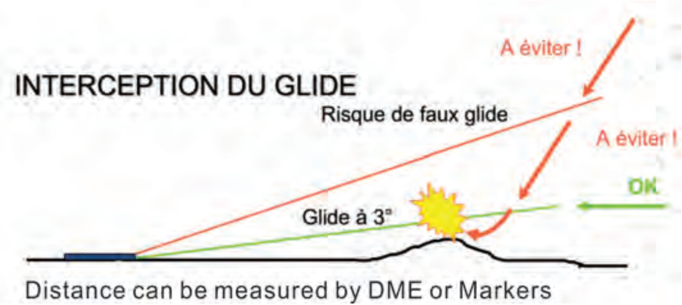


Fig. 94: GP trajectory

GP Trajectory

The place where DDM $= 0$ is in fact some surface of a revolution cone, when the aircraft pass the threshold the GP indicator will become unstable.

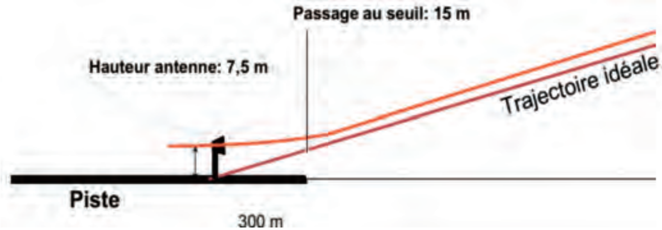


Fig. 95: GP trajectory

Markers

Markers are used to for distance and altitude measurement during the 75 MHz.

Three types of markers exists,

- Outer Marker (OM), 400 Hz, low, blue.
- Middle Marker (MM), 1300 Hz, medium, amber.
- Inner Marker (IM), 3000 Hz, high, white.

Markers

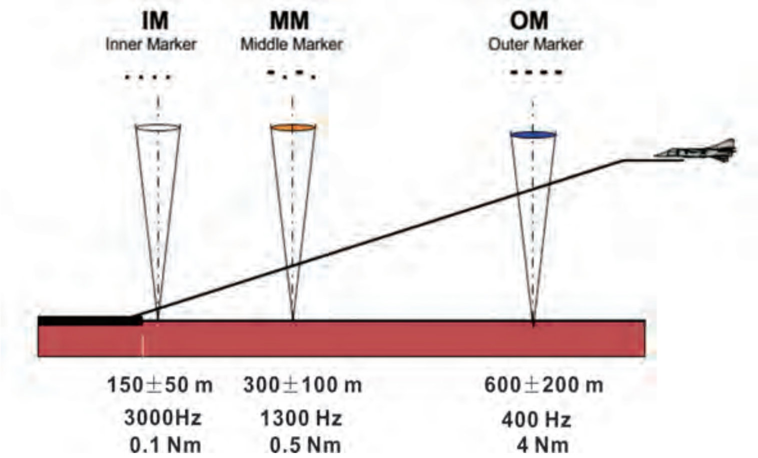


Fig. 96: GP trajectory

ILS CDI

Fig. 97: ILS CDI display

HSI

Fig. 98: HSI display

PFD and ND

Fig. 99: PFD and ND display

ILS Application

ILS is used during the approach and landing,

- Identified the ILS by certain frequency (with correct heading), the ILS information is displayed by CDI, HSI, PFD and ND.
- Align with LOC, prepare the aircraft with velocity, configuration, etc.
- Align with GP, control the altitude and distance with DME and Markers.
- After the HD, the pilot will finish the landing by visualization.

Outline

History

Brief history of GPS (Global Positioning System),

- 1973: Decision to develop a satellite navigation system base on TRANSIT.
- 1978: NAVSTAR (Navigation System with Timing And Ranging), now known as GPS was lunched, with 11 satellites (1975-1985).
- 1980: Decision to expand GPS. At first 18 satellites should be operate, and atomic clock onboard was activated.
- 1983: After Korean Airline was shoot down by Soviet Union, GPS was declassified by Present Reagan. And GPS was allowed to be used by civil aviation.
- 1986: The accident of "Challenger" meant a drawback of the GPS program. The Delta rockets take the job for transportation the GPS satellites.

History

- 1990-1991: Temporal deactivate SA(Selective Availability) during the Gulf War. On 01/07/1991 the SA was activated again.
- 1993: GPS can be freely used by civilian in worldwide.
- 1995: 24 GPS satellites are complete.
- 1996: SA would be stopped according to the order from President Clinton. More accurate service could be provided for civilian applications.
- 2000: On 02/05/2000, SA was officially stopped. The GPS positioning service can achieve 10-15 meters (100 m with SA functional).
- 2004: Launch of the 50th GPS satellites.
- 2005: New GPS satellites was launched, which supports new military M signal and L2C frequency.

History

ICAO definition of GNSS: GNSS is defined as a system able to estimate the position and time of the user, and that includes one or several satellite constellations, onboard receivers, and an integrity monitoring system, augmented if necessary, in order to reach required navigation performance for the desired aircraft operation.

Note GPS performance is not sufficient to be a GNSS by itself.

In civil aviation world, the GNSS work includes,

- Adapt the different GNSS system: GPS, BEIDOU, GIONASS, GALILEO.
- Define the capacity of the receivers.
- Define the capacity of surveillance system: integrity, continuity.
- Augmentation systems.

Space Segment

The GPS system space Constellation segments have,

- Minimum: 24 satellites
  - Orbit radius of 26600 km (altitude 20200 km).
  - Orbit repetition: 12 siderial hours.
  - Ground track repeat every 24 siderial hours (23 h 56 m 04.0905 s).
- Each satellite has 3 or 4 atomic clocks (Cs or Rb, the latest ones have Rb).
- Two frequencies are used
  - L1: 1575.42 MHz in ARNS (Aeronautical Radio Navigation Service) band.
  - L2: 1227.60 MHz not in ARNS band.

Ground Segment

Ground segment includes: Control segments and user receiver. The function of the control segments,

- Control the characteristics of the transmitted signals from each satellite.
- Compute the ephemerides and satellite clock corrections.
- Unload the navigation message to each satellite.

The structure of the control segments,

- 1 Master control station
- Control stations
- Upload stations

User receivers are used for navigation solution.

Outline

Sensor

Air data sensors and ADC

Inertial sensors and systems

Radio navigation

GPS/GNSS

§ Introduction

§ GPS principle

§ Error and precision

Measurement Principle

GPS can measure the distances and the velocity.

- The distance are essentially the result of propagation delays between the satellite and the receiver.
- The velocities are the Doppler offset of the received signals.

The distance measurements, which are the basic functions of the normal receiver, can be provided through code delay tracking and phase tracking. And code delay tracking is more common.

- A DLL (Delay Lock Loop) is used to estimate the time delay between the incoming PRN (pseudo random noise code) code and the local PRN code.
- Code pseudorange measurements are thus the estimated PRN code delay multiplied by the speed of light.

Measurement Principle

To finish the navigation solution, 4 satellites must be needed, all calculations will referred to WGS84 system.

$$\rho_i = \sqrt{(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2} + c\Delta t$$

- ρ_i: pesudorange, $i = 1, 2, 3, 4$.
- x, y, z: satellite coordinates.
- x_i, y_i, z_i: receiver coordinates.
- c: speed of light.
- Δt: propagation delay between the satellite and the receiver.

Coordinate Reference

WGS84: World Geodetic System - 1984.

- Axes
  - O: mass center of the Earth.
  - Z: through O and Conventional Terrestrial Pole which is the average position of the pole between 1900 and 1905.
  - X: intersection between the Equator and the Greenwich meridian.
  - Y: complete the frame.
- Reference ellipsoid
  - Center = 0 wgs84.
  - 1/2 grand axe a = 6378137 m
  - 1/2 petit axe b = 6356752.3142 m

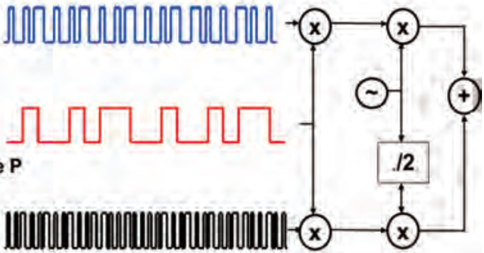
Time Frame

The GPS time is computed from a set of atomic clocks at the US Observatory. It INGORES THE UTC "Leap seconds". The UTC time (Coordinated Universal Time) can be compute from the information of the "leap seconds" in the navigation message.

The GPS was initialized with UTC on 06/01/1980.

Signal

- **Code speudo- Aléatoire : code C/A**
  - Débit 1.023 mHz
  - Période 1 ms
  - Bande L1
- **Message de Navigation**
  - Débit 50 bits/sec
  - Bande L1 et L2
- **Code speudo-aléatoire : code P**
  - débit 10.23 mHz
  - période 7 jours.
  - bande L1 et L2 (P(Y))



Signal

The navigation message consist of,

- 50 bps.
- 25 frames of data, each frame consists of 1500 bits.
- Each frame has 5 subframes, each subframe consists of 300 bits, where subframe 1, 2 and 3 has the same data format in all 25 frames. This means the receiver can obtain the critical satellite data with in 30 seconds.
  - Subframe 1: clock correction, accuracy parameters and health status.
  - Subframe 2 and 3: ephemeris, which is used to determine the precious satellite position.
  - Subframe 4 and 5: almanac for all satellites, low precision clock corrections, ionospheric model and UTC. Those message can be restored by the user receiver and could be valid for several days.

Signal

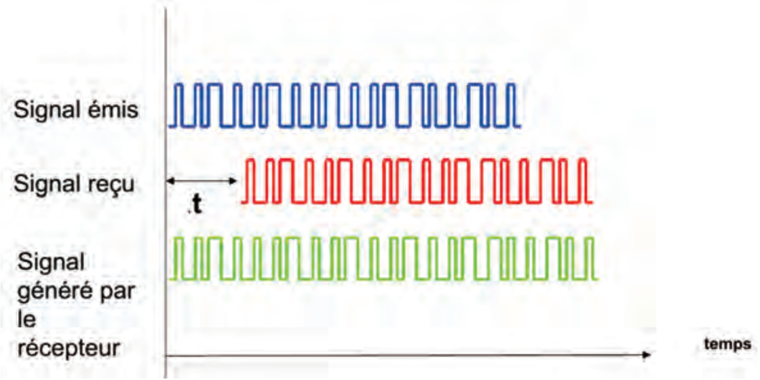


Fig. 100: PRN code correlation

Outline

UERE

UERE: User Equivalent Range Error, represents the uncertainty affecting the pseudorange measurements as observations used in the PVT computation. The errors are:

- Satellite clock error: 1 km
- Ionospheric delay: 0.15 - 50 m
- Tropospheric delay: 2 - 30 m
- Multipath; 0 - 150 m
- Other noise: 1 m

User receiver error:

- Clock error: 300 m
- White noise: 1 m

UERE

The errors after correction,

Horloge Satellite	1.5 m
Ephéméride	2.5 m
Iono	5.0 m
Tropo	0.5 m
Multitrajet	0.6m
Bruit récepteur	0.3
UERE	8 m

DOP

DOP: Dilution of Precision. DOP links the UERE with the positioning uncertainty.

The link between the UERE and positioning uncertainty, take the 3D positioning error for example, is

$$\sigma_{3D} = PDOP \times \sigma_{UERE}$$

PDOP is the the most common value for civil users, has a best case value of 1, higher number being worse. The best PDOP would occur with one satellite directly overhead and three others evenly spaced about the horizon. PDOP could theoretically be infinite, if all the satellites were in the place.

DOP

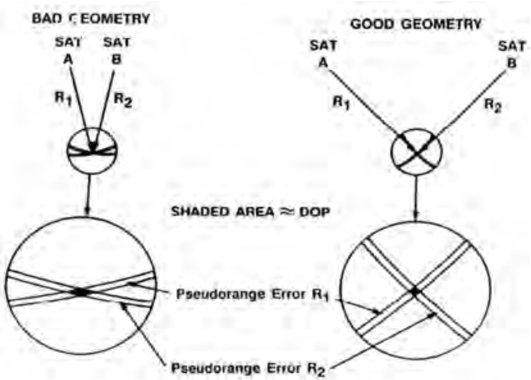


Fig. 101: Satellites geometry

Augmentation system

ABAS: Aircraft Based Augmentation System.

GBAS: Ground Based Augmentation System.

SBAS: Satellite Based Augmentation System.

- WAAS: Wide Area Augmentation System, US
- EGNOS: Europe Geostationary Navigation Overlay Service
- MSAS (MTSAT): Multifuncitonal transport Satellite based Augmentation system, Japan
- GAGAN: GPS and GEO Augmented Navigation, India

Augmentation System

		ABAS	SBAS	GBAS
En route		*	*	
Terminal		*	*	
Approche	Non précision		*	*
	Précision			*
	Interrompue		*	*
Sol				*
Départ			*	*

Fig. 102: Satellites geometry

Other GNSS Systems

GLONASS

GALILEO

BEIDOU