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Avionics Made Simple

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AVIONICS MADE SIMPLE

By

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ABOUT THE AUTHOR

Mouhamed Abdulla received the B.Eng. degree in Electrical Engineering in December-2002 from Concordia University, Montréal, Québec, Canada. Presently, he is on the verge of finishing his M.Eng. in Aerospace Engineering through the direct supervision of Dr. Luis Rodrigues (***luisrod@encs.concordia.ca***) also at Concordia University. Mouhamed is currently employed at IBM Canada Ltd. as a Support Specialist for IBM/Lenovo products. He has professional affiliations, including, among others, IEEE, AIAA, and OIQ. His research interests include VLSI design, VLSI process technology, DSP, and Avionics. He can be reached at ***mabdulla@ca.ibm.com***.

To the most precious person of my life:
To My Mother

ACKNOWLEDGMENT

First and foremost, I would like to express my sincere gratitude and respect to the late Dr. Jaroslav V. Svoboda. He was my first contact to this exciting field, and a true mentor to the many students that he had over the years including myself. May his soul rest in peace and he will always be with us in our hearts and thoughts. I am also grateful to my supervisor Dr. Luis Rodrigues for his guidance, support and encouragement. I also like to thank Dr. Marius Paraschivoiu for giving me the chance to work on this project. Further, I would like to thank Professor Anwar Abilmouna for extremely insightful information on avionic system design that he acquired over the many years in industry. Last but not least, I would like to thank Ms. Leslie Hosein for always taking the time to answer my many questions on administrative issues and deadlines.

PREFACE

The purpose of this book is to present aerospace electronic systems, also known as avionics, in a logical and comprehensible fashion. In fact, when we talk of avionics we usually refer to the following 20 acronyms:

ADF	**TACAN**	**LORAN-C**	**GPS**	**ILS-GS**[0]
NDB	**VORTAC**	**OMEGA**	**ALS**	**MB**
VOR	**RNAV**	**INS / IRS**	**VASIS**	**MLS**
DME	**RMI / HSI**	**DNS**	**ILS-LOC**	**DGPS**

These acronyms form the basics and fundamentals of avionics. Now you might ask yourself: *what new is this work bringing?* After all many authors with large amount of experience in the field have written books on the subject; many conference papers have tested and studied aspects of avionics; hundreds if not thousands of websites on the worldwide web have avionic related documents.

To answer the question above I need to mention that it is definitively true that information exist, and naturally I have used relevant information in this book from the above sources. However, most of the information sources available to the world, i.e. books, papers, and websites, come short in the following:

- They don't include all basic avionic systems in a single piece of work. Usually the reader must look at different locations to get the fundamentals of a system.

- Even if by luck we come across a work that does include relevant information, it usually fails in organization, presentation, and optimization of the data.

- Many books are filled with so much information that as an example by the *20th page* on a specific avionic hardware, we will completely forget the main purpose of the system. In other words, we would not even know what output is expected using that specific avionics. Most probably in such a scenario, the author either diverged to a different side-topic or maybe he/she might have concentrated on a specific aspect of the system and forget the bigger picture.

Because of the reasons outlined above, among others, I decide to once and for all explain avionics in a systematic fashion with clear and concise terms. Consequently, this book should also be proven to be effective as a refresher on a particular technology. Say in five or even ten years from now, we could simply target the chapter and section of interest and obtain the fundamentals of a system in matter of minutes [*fundamentals usually don't change with time or maybe change with a slow rate; data on the other hand would most probably be outdated by then]*.

In is often said by professionals in the field of literature and language, that to teach *someone [i.e. students]* about *something [i.e. basic avionics]* one needs to use the method of questioning. In fact, this logical method is based on six interrogations also known as 5W+H:

- **WHAT:** What is the purpose of this system? What is the useful output that I am getting after using this system?

- **WHO:** Who is permitted to use this system? Civilian? Military? or Both?

- **WHERE:** Where is this system located? On the ground? In the aircraft? In space?

- **HOW:** How does this system work? What are the logical steps [block diagrams] in the operation of this system?

- **WHY:** Why is this system good [advantages]? or Why is it bad [disadvantages]?

- **WHEN:** When was this system certified as a liable avionic tool? What is the future of this system? Will it be phased-out? or Will it survive? And if so for how long?

I will try as much as possible to provide sufficient answers to these questions. In fact, the strategy and logic used to provide simple answers to the above interrogations are as follows:

- I will first look for the answers from the class notes of our very own Concordia professor, the late Dr. Jarslov Svoboda.
- In case I don't find the answers there or that I need a second opinion or that I am simply not sure of the integrity or validity of the of the data due to fast innovations of avionic technologies, I will refer to other sources as enumerated in the reference section of this book.

I am pleased and honored to have Dr. Luis Rodrigues as my supervisor for this work. His contribution consists mainly on reviewing the topics; provide constructive comments, and enforce the rules and regulations in regard to copyrights.

The book is written in point format approach without excessive details so that it is easy to read and memorize. As for the layout of the information, it is presented in an organized and an optimized fashion. In the sense that if different systems with similar purpose are explained, then a symmetrical structure will be outlined to simplify the comparison study among technologies.

Moreover, a major emphasis is given to the illustrations and diagrams to facilitate the understanding of the material. Most of the diagrams were illustrated using Visio Professional 5.0 available from Visio Corporation. To be more specific, the illustrations used throughout this book are classified into 7 types:

- Illustrations ***created fully with Visio using my personal understanding*** of a topic.
- Illustrations that I have ***seen in class notes***, and then ***reproduced exactly the same thing using Visio***.

- Illustrations that I have ***seen in class notes***, and then ***modified it using Visio***. Usually when I recreate a figure that I have seen in a related source [class notes or websites], I will modify it by either making it simple or even more complex so that it becomes complete yet easy to understand.

- Illustrations that I have ***seen in class notes***, and then ***recreated fully the same thing using Visio***, ***with modifications*** to reflect my perception of the subject.

- Illustrations ***found on the worldwide web*** available to the general public.

- Illustrations that I have ***seen on the worldwide web***, and ***then modified it using Visio***.

- Illustrations that I have ***seen on the worldwide web***, and then ***recreated fully the same thing using Visio***, ***with modifications***.

Also, on occasions, a programming code is used to facilitate quick calculation for a specific transformation. The code will be based on the Matlab programming language available from MathWorks Inc.

As far as the content is concerned, it is partitioned into two major sections: *Preliminary* and *Avionics.* The *Preliminary* section does not discuss avionic systems; it is there to assist the reader on general aerospace facts that could be useful once the avionic section is reached. The 20 acronyms listed above would be explained in the *Avionics* section, which in principle forms the essence of this book. Now since the major theme of this work is efficiency, then naturally we should deduce that avionic systems would not be discussed equally. In other words, systems that have retired or that are on the verge of being phased-out will be discussed briefly; where as systems that are important today and have promising improvement for the future will be explained in-depth.

Finally, readers should realize that the work was prepared to be self-contained, such that no references or prerequisites are required or assumed to understand the principal of a given technology. In fact, all type of readers coming from different professional background should normally understand the topics effortlessly. Obviously, some may choose to thrive more in a specific subject which then would be quite normal to reference specialized and advanced literatures.

ACRONYMS

Numbers	**2D**	Latitude and Longitude
	3D	Latitude, Longitude, and Altitude
A	**A**	Alert Area
	ABS	Automatic Breaking System
	A/C	Aircraft
	ADC	Air Data Computer
	ADF	Automatic Direction Finder
	ADIZ	Air Defense Identification Zone
	AFIS	Airborne Flight Information System
	AGL	Above Ground Level
	AI	Airspeed Indicator
	AKA	Also Known As
	A/L	Approach Landing
	ALS	Approach Lighting System
	ALT	Altitude
	AM	Amplitude Modulation
	ARINC	Aeronautical Radio Inc.
	ARSA	Airport Radar Service Area
	ARTCC	Air Route Traffic Control Center
	ASRA	Aviation Safety Reporting System
	ATA	Airport Traffic Area
	ATC	Air Traffic Control
	ATCTC	Air Traffic Control Tower Center
C	**C**	Center
	C/A	Course Acquisition Modulation
	CAS	Calibrated Airspeed
	CAT	Category
	CDI	Course Deviation Indicator
	CG	Center of Gravity
	CIV	Civilian
	Cs	Cesium
D	**DA**	Drift Angle
	DB	Database
	DG	Directional Gyroscope
	DGPS	Differential Global Positioning System
	DH	Decision Height
	DME	Distance Measuring Equipment
	DNS	Doppler Navigation System
	DoD	Department of Defense
	DoT	Department of Transportation
	DR	Dead Reckoning
	DSARC	Defense System Acquisition and Review Council
	DST	Daylight Saving Time
E	**E**	East
	EAS	Equivalent Airspeed
	ECEF	Earth Centered Earth Fixed
	EFIS	Electronic Flight Instrument System
	EHF	Extremely High Frequency
	ELF	Extremely Low Frequency
	ELT	Emergency Locator Transmitter
	EM	Electromagnetic
	EMI	Electromagnetic Interference
	ETA	Estimated Time of Arrival
	EU	European Union
F	**FAA**	Federal Aviation Administration
	FAF	Final Approach Fix
	F/C	Flight Compartment
	FCC	Federal Communications Commission or Flight Control Computer
	FL	Flight Level
	FM	Frequency Modulation
	FMS	Flight Management System
	FREQ	Frequency
	FSS	Flight Service Station
G	**GLONASS**	Global Navigation Satellite System
	GMT	Greenwich Mean Time
	GND	Ground
	GPS	Global Positioning System
	GS	Ground Speed
	GS⁰	Glideslope
H	**HDG**	Heading
	HF	High Frequency
	HSI	Horizontal Situation Indicator
	HUD	Heads Up Display
	HW	Hardware
I	**IAF**	Initial Approach Fix
	IAP	Instrument Approach Procedures
	IAS	Indicated Airspeed
	IATA	International Air Transport Association
	ICAO	International Civil Aviation Organization
	ICAT	International Center for Air Transportation

	ID	Identification
	IFATCA	International Federation of Air Traffic Controller Associations
	IFR	Instrument Flight Rules
	ILS	Instrument Landing System
	IM	Inner Marker
	INS	Inertial Navigation System
	IRS	Inertial Reference System
	ITU	International Telecommunication Union
K	**KTS**	Knots
L	**L**	Left
	LAAS	Local Area Augmentation System
	LAT	Latitude
	LCD	Liquid Crystal Display
	LF	Low Frequency
	LOC	Localizer
	LON	Longitude
	LOP	Line of Position
	LORAN-C	Long Range Navigation (revision-C)
	LOS	Line of Sight
	LST	Local Standard Time
M	**MB**	Marker Beacon
	MDA	Minimum Descent Altitude
	MF	Medium Frequency
	MIL	Military
	MIT	Massachusetts Institute of Technology
	MLS	Microwave Landing System
	MM	Middle Marker
	MOA	Military Operations Area
	MSL	Mean Sea Level
	MTR	Military Training Route
N	**N**	North
	NASA	National Aeronautics and Space Administration
	NAV	Navigation
	NAVAID	Navigational Aid
	NAVSTAR	Navigation System with Timing And Ranging
	NDB	Non Directional Beacon
	NiCd	Nickel Cadmium
	NiH_2	Nickel Hydrogen
	NM	Nautical Miles
O	**OM**	Outer Marker
	OMEGA	Optimized Method for Estimated Guidance Accuracy
	OS	Outer-Space
P	**P**	Prohibited Area
	PCA	Positive Control Area
	PED	Portable Electronic Device
	P/O	Phased Out
	PRC	Pseudo Random Code
	P(Y)	Precise Encrypted Modulation
Q	**QFE**	Pressure at Field Elevation
	QNE	Pressure at Standard Sea Level
	QNH	Pressure at Nautical Height
R	**R**	Restricted Area or Right
	RA	Radio Altimeter
	RAPCON	Radar Approach Control Facility
	RATCC	Radar Air Traffic Control Center
	Rb	Rubidium
	R&D	Research and Development
	RMI	Radio Magnetic Indicator
	RNAV	Random or Area Navigation
	RPS	Revolutions Per Second
	RVR	Runway Visibility Range
	Rx	Receiver
S	**S**	South
	SA	Selective Availability
	SAT	Satellite
	SATCOM	Satellite Communications
	SHF	Super High Frequency
	SLF	Super Low Frequency
	SM	Statue Miles
	SVN	Satellite Vehicle Number
T	**TACAN**	Tactical Air Navigation System
	TAS	True Airspeed
	TCA	Terminal Control Area
	TCAS	Traffic Alert and Collision Avoidance System
	TCCA	Transport Canada Civil Aviation
	TDP	Touchdown Point
	TK	Track
	TRACON	Terminal Radar Approach Control
	Tx	Transmitter
U	**UHF**	Ultra High Frequency
	ULF	Ultra Low Frequency
	US	United States of America
	USAFSC	US Air Force Space Command

	USNO	US Naval Observatory
V	**VASIS**	Visual Approach Slope Indicator System
	VFR	Visual Flight Rules
	VHF	Very High Frequency
	VLF	Very Low Frequency
	VOR	VHF Omni-directional Range
	VORTAC	VOR & TACAN
	VSI	Vertical Speed Indicator
W	**W**	Warning Area or West
	WA	Wind Angle
	WAAS	Wide Area Augmentation System
	WGS-84	World Geodetic System of 1984
	WMS	WAAS Master Station
	WPT	Waypoint
	WRT	With Respect To
	WS	Wind Speed
	WXR	Weather Radar System

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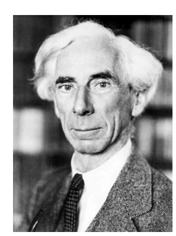
Chapter 1

Introduction

There is much pleasure to be gained
from useless knowledge.

— Bertrand Russell



1.1 Air Navigation

Air Navigation (NAV) is the process of directing the movement of an aircraft (A/C) from one point to the other. It involves the control of position, direction, and speed of an A/C with respect to time.

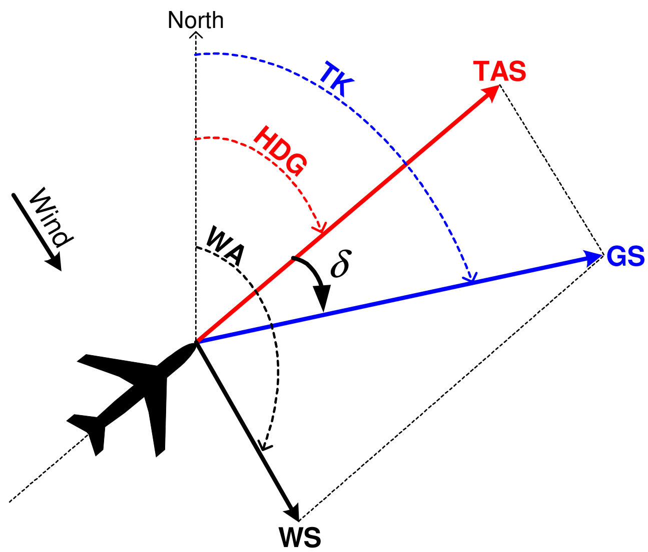
1.2 NAV Methods

- **Pilotage:** Early method of NAV based on visual reference to landmarks.

- **Dead Reckoning (DR):** NAV by extrapolating. That is, determining the present position through the knowledge of a previous reference position.

  1) Obtain an estimate of the Ground Speed (GS).
  2) Integrate over-time to obtain the position.

$$x = \int \mathrm{GS}(t)\,dt \tag{1.1}$$



TAS: True Airspeed
HDG: Heading Angle
GS: Ground Speed
TK: Track Angle
WS: Wind Speed
WA: Wind Angle
δ: Drift Angle

Figure-1.1 GS estimation

$$\begin{aligned} \vec{GS} &= \vec{TAS} + \vec{WS} \\ \{GS \angle TK\} &= \{TAS \angle HDG\} + \{WS \angle WA\} \end{aligned} \tag{1.2}$$

- **Radio NAV:** NAV through the use of wireless communication signals broadcasted by Ground (GND) or A/C based radio station.

- **Celestial NAV**: NAV in reference to heavily bodies, such as: sun, moon, planets, stars, etc.

- **Inertial NAV:** NAV based on double integrating the A/C acceleration measured using airborne equipments.

$$x = \iint a(t)\,dt_1 dt_2 \tag{1.3}$$

- **Satellite NAV:** NAV through the use of data broadcasted by a Satellite (SAT) based transmitter.

1.3 History of Air NAV

- **1910's (WWI):**

  1) *Compass*
  2) *Altimeter*: Instrument to measure height above a reference.
  3) *Airspeed Indicator*
  4) *Watch*
  5) *Pilotage*
  6) *DR*

- **1920's:**

  1) *Blind Flying*: i.e. without looking from the cockpit window.

  2) *Directional Gyroscope*: Instrument that sense angular motion using momentum of a spinning mass with respect to (w.r.t) 1 or 2-axes orthogonal to the spin axis.

  3) *Artificial Horizon*: Gyro operated flight instrument that shows the inclination of an A/C w.r.t. a horizon bar.

  4) *Advanced DR*

- **1930's:**

  1) *Basic-T*: Standardization of flight instruments.
  2) *Electronic NAV*
  3) *Radio Communication*
  4) *Autopilot*

- **1940's (WWII):**

1) *Celestial NAV*: Progress in long-range NAV.

2) *Radio Communication*

3) *Radar:* System that uses radio waves for detecting and locating objects in space.

❖ Turn on radar Transmitter (Tx).

❖ Radar sends a radio wave beam to the object.

❖ Turn off radar Tx and turn on its Receiver (Rx).

❖ Radar detects the echo reflected by the object.

❖ Time for the traveled beam from the object to the radar is captured as well as the Doppler shift of the echo.

❖ Since radio wave travel with the speed of light *c*, hence position is known; and the speed of the object is also known through the Doppler shift data.

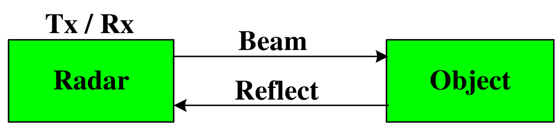


Figure-1.2 Radar system

$$x = c\ t \tag{1.4}$$

4) *Transponder*: Communication system that has a combined Tx and Rx. Used in A/C and SATs for 2-way communications.

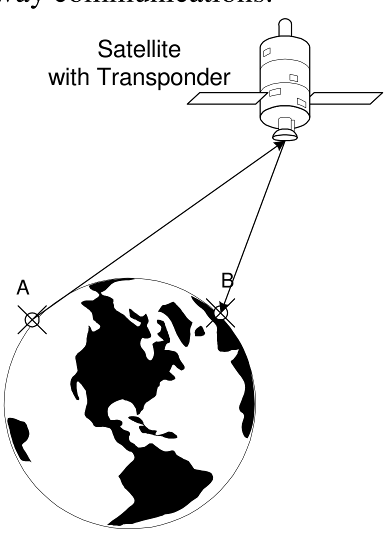


Figure-1.3 SAT system with an integrated transponder

- **<u>1950's & 60's:</u>**

    1) *Jet-Age*

    2) *Avionics:* New term meaning electronic NAV was standardized.

    3) *Avionic Systems:* Progress in electronic air NAV.

        - Automatic Direction Finder (ADF): System that tells us where the A/C is located.

        - Very High Frequency (VHF) Omni-directional Range (VOR): System that tells us the A/C angle[1] w.r.t to a GND station.

        - Tactical Air Navigation System (TACAN): Military (MIL) system used to provide bearing and distance between the A/C and a GND station.

        - Integrated VOR & TACAN system (VORTAC): GND station with VOR and TACAN antennas.

        - Instrument Landing System (ILS): System that guides the A/C for an ideal landing.

        - Inertial Navigation System (INS): Airborne system that gives continuous A/C position information through DR.

    4) *Sophisticated Autopilot System*

- **<u>Today:</u>**

    1) *Space-Age*

    2) *Integrated Flight Control*

    3) *Flight Management System (FMS)*: System that can fly the A/C.

    4) *Electronic Flight Instrument System (EFIS):* Touch-operated screen showing all flight and engine instruments required to fly an A/C with audio capabilities.

    5) *Heads-Up Display (HUD):* Cockpit window will display navigational information, therefore no need to incline to observe data on dashboard but rather look straight to the window.

[1] *Angle* information or *bearing* or *azimuth* are similar terms and could be used interchangeably.

6) *Microwave Landing System (MLS):* MIL system that does not require a straight flight path in order to land.

7) *Long Range Navigation (LORAN-C):* System used to determine A/C position.

8) *Optimized Method for Estimated Guidance Accuracy (OMEGA):* System used to determine A/C position.

9) *Global Positioning System (GPS):* System used to determine A/C position using SATs.

10) *Air Traffic Control (ATC):* Promoting safety an order in airspace.

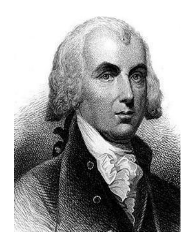
11) *Free-Flight Concept:* The idea is based on letting every airplane in sky to know of each other so as to increase traffic awareness, avoid collisions, and reduce ATC workload.

Chapter 2

Basic Concepts

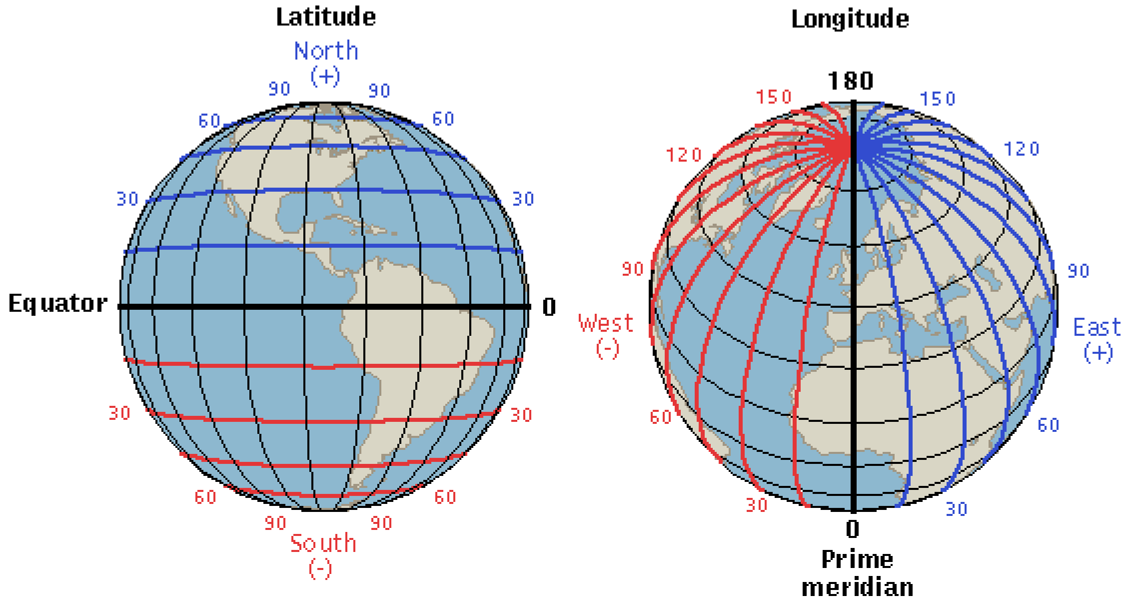
Knowledge will forever govern ignorance:
And a people who mean to be their own
Governors, must arm themselves with
the power which only
knowledge gives.

— James Madison



2.1 Earth Coordinate Systems

- **<u>Latitude / Longitude:</u>** Location of any point on earth is defined by its Latitude (LAT) and Longitude (LON) coordinates.



LAT:	90° North ↑ 0° Equator ↓ 90° South
LON:	180° West ← 0° meridian → 180° East

Figure-2.1 Earth coordinate system ***left:[K4-1]***

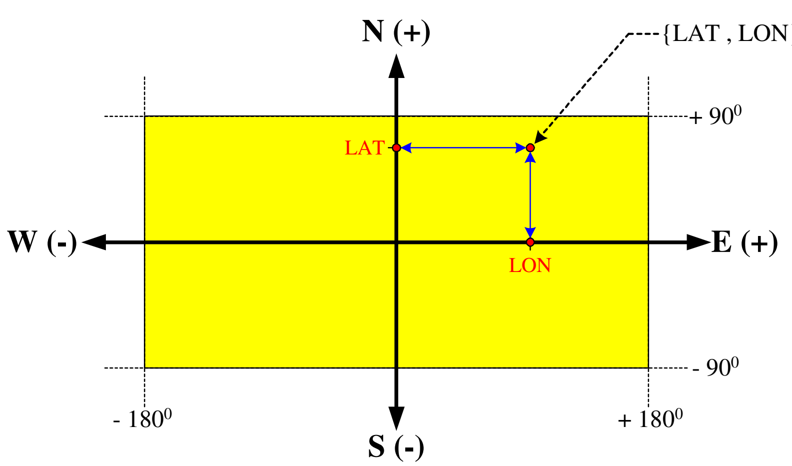


Figure-2.2 Sign convention used for a 2D mapping of the earth surface

1) *Transformation from hour/minute/second to decimal format*[2]*:*

$$\text{decimal} = \pm\left\{\frac{\left(\left(\text{seconds}/60\right)+\text{minutes}\right)}{60}+\text{hours}\right\} \qquad (2.1)$$

[2] The ± in the formula is assigned as per the sign convention of Figure-2.2. A Matlab code for this transformation is available in Appendix A.

2) *Transformation from decimal to hour/minute/second format*[3]*:*

$$\boxed{\begin{array}{c} a = |\text{decimal}| \\ \text{hours} = \text{integer}(a) = \text{i.e. take only the integer part of } a \\ b = (a - \text{hours}) \times 60 \\ \text{minutes} = \text{integer}(b) = \text{i.e. take only the integer part of } b \\ \text{seconds} = (b - \text{minutes}) \times 60 \end{array}} \tag{2.2}$$

$$\textit{Montréal} \;\; / \;\; \textit{Québec} \;\; / \;\; \textit{Canada}$$

$$\left\{ \begin{array}{ll} LAT: & \underbrace{45^0\ 30'}_{\text{North}} = \underbrace{45.5^0}_{\text{North}} = +45.5^0 \\ LON: & \underbrace{73^0\ 35'}_{\text{West}} = \underbrace{73.583^0}_{\text{West}} = -73.583^0 \end{array} \right\}$$

- **<u>Great Circle:</u>** This surface line is used in *long-distance-flying*. It is based on the intersection of a sphere and a plane through its center. In other words, to obtain the shortest distance between any 2 points on the earth surface, we must have a plane that cuts these 2 points and the earth center.

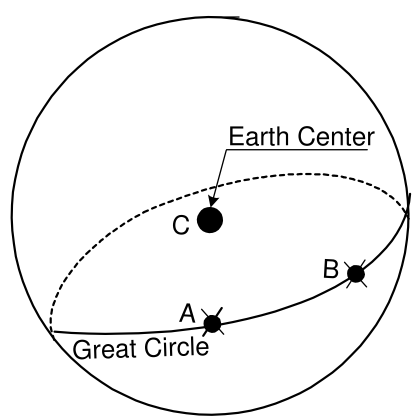


Figure-2.3 Great circle *[K6-1]*

$$\begin{aligned} D &= \left(\frac{R\pi}{180}\right) \cos^{-1}\left\{\sin(LAT_1)\sin(LAT_2) + \cos(LAT_1)\cos(LAT_2)\cos(LON_1 - LON_2)\right\} \\ &= (111.320)\ \cos^{-1}\left\{\sin(LAT_1)\sin(LAT_2) + \cos(LAT_1)\cos(LAT_2)\cos(LON_1 - LON_2)\right\} \end{aligned} \tag{2.3}$$

[3] North/South or East/West is assigned as per the direction convention of Figure-2.2. A Matlab code for this transformation is available in Appendix B.

R: Earth radius $[6,378.137 \text{ km}]$.
D: Shortest distance between 2 points on the earth surface $[\text{km}]$.
LAT_1: Latitude of the 1st point on the earth surface $[\text{degrees}]$.
LAT_2: Latitude of the 2nd point on the earth surface $[\text{degrees}]$.
LON_1: Longitude of the 1st point on the earth surface $[\text{degrees}]$.
LON_2: Longitude of the 2nd point on the earth surface $[\text{degrees}]$.

- **Rhumb Line:** This surface line is used in *short-distance-flying*. It is based on traveling between 2 points by intersecting the meridian at a constant angle.

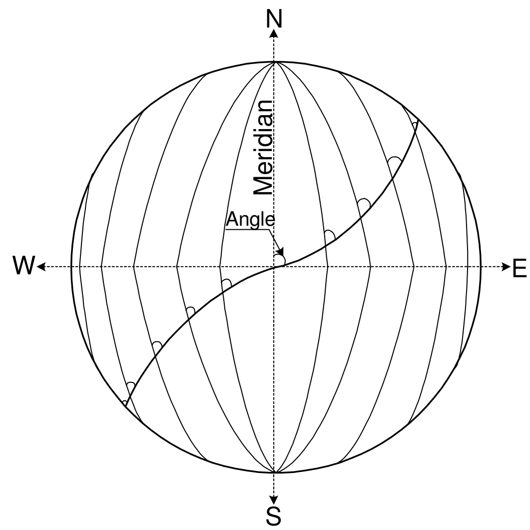


Figure-2.4 Rhumb line *[K3-1]*

- **Time:** Earth is divided into 24 time zones.

1:	Earth speed = 1 revolution / 24 hrs
2:	$\left\{\begin{matrix} 1 \text{ revolution} = 360^\circ & \rightarrow & 24 \text{ hrs} \\ \chi & \rightarrow & 1 \text{ hr} \end{matrix}\right\} \Rightarrow \chi = 15^\circ$
3:	15° LON $\equiv$ 1 hr

(2.4)

1) *Daylight Saving Time (DST):* During the summer, zonetime is set forward by 1 hour.

❖ Not all countries observe DST.

❖ Even if countries use DST, some cities or provinces[4] within that country will not take into consideration DST.

[4] As an example, Canada uses the DST during summer; however the province of Saskatchewan does not.

- The interpretation of summer differs from one nation to the other; and therefore, the beginning and end dates of DST is non-standardized and hence, varies from one country to the other.

- Some countries may decide to change[5] the beginning and end dates of DST for various reasons.

- Every now and then some countries decide to implement the DST system. On the other hand, other nations that previously had DST may suddenly stop using it.

2) *Local Standard Time (LST):* It is the local time in a specific geographical area.

3) *Greenwich Mean Time (GMT):* Universal standard time is referred to as GMT[6], Zulu or Z time. It is extremely important to realize that GMT never changes and DST has no effect whatsoever on GMT. Because of this important characteristic, GMT is mainly used in aviation as a time reference all across the world.

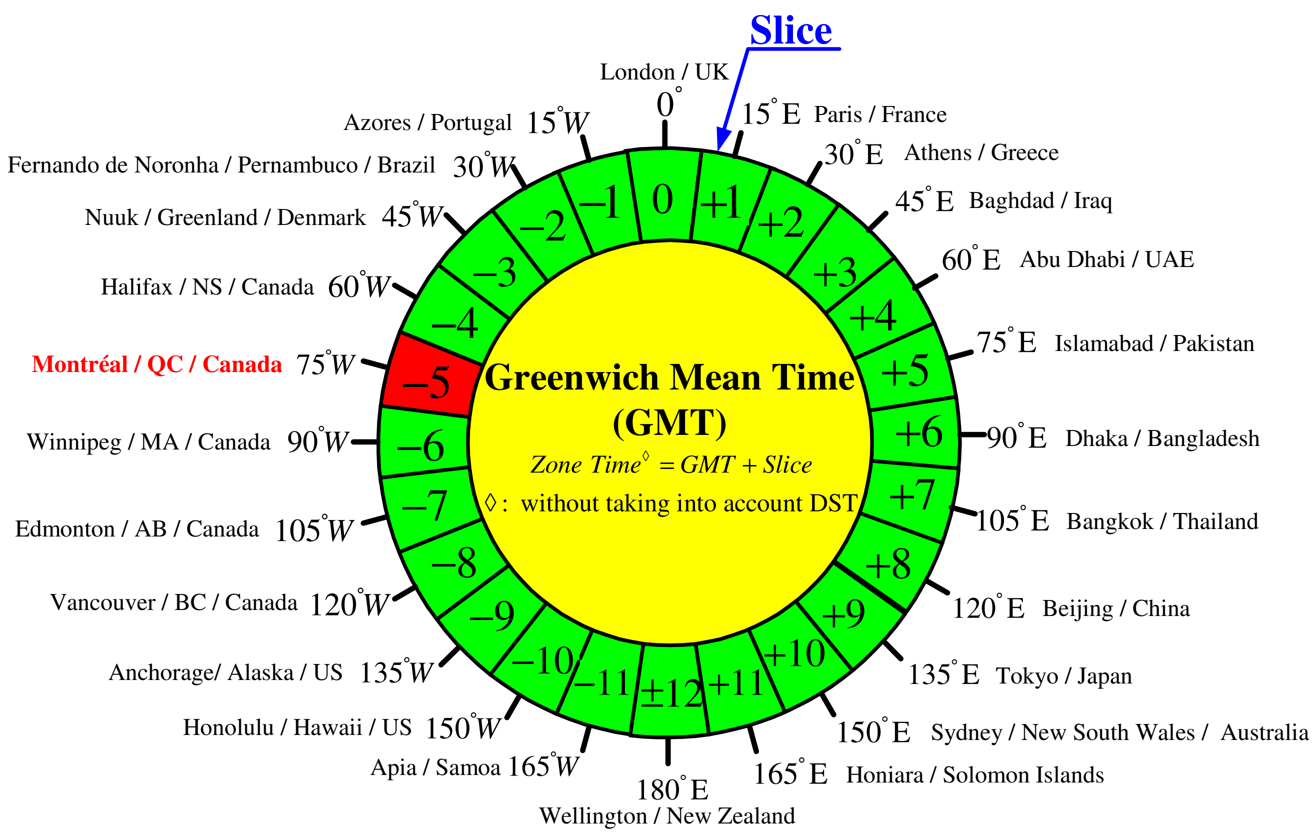


Figure-2.5 GMT standard ***[K3-2]***

[5] As an example, the Energy Policy Act of 2005 signed by US President George W. Bush will extend DST by 4 weeks stating *March-11-2007*. The provincial governments of Québec and Ontario have decided to adapt this change as of *2007* in order to remain in synch with neighboring US.

[6] GMT can be observed on: ***http://wwp.greenwichmeantime.com***

- **Nautical Mile (nm) / Knots (kts):**

1:	$\text{Earth Radius} = r = 6{,}378.137 \text{ km}$ $\text{Earth Circonference} = 2\pi r = 40{,}075.017 \text{ km}$	
2:	$\left\{\begin{array}{l} 360^\circ = (360 \text{ deg})(60 \text{ min/deg}) = 21{,}600 \text{ min} \rightarrow 40{,}075.017 \text{ km} \\ \qquad 1 \text{ min} \rightarrow \chi \end{array}\right\} \Rightarrow \chi = 1.852 \text{ km}$	(2.5)
3:	$1 \text{ minute} = 1 \text{ nm} = 1.852 \text{ km}$ $1 \text{ knot} = 1 \text{ nm/hr} = 1.852 \text{ km/hr}$	

2.2 Earth Mapping Systems

Projection methods are used to represent the 3D spherical earth on a 2D flat surface.

- **Lambert Conic Projection:** This projection method is used in *long-distance-flying*. The meridians are straight lines that converge to the pole. Whereas the parallels are concave curves. Also, the scale is uniform throughout the map.

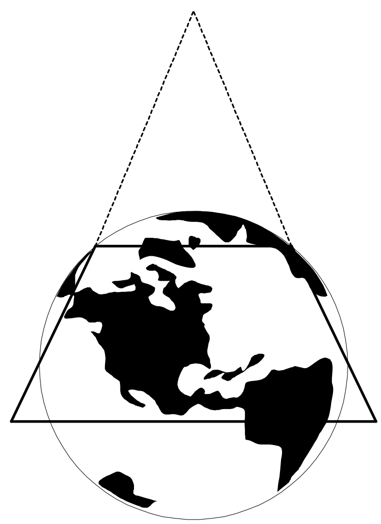


Figure-2.6 Lambert conic projection *[K6-2]*

- **Transverse Mercator Projection:** This projection method is used in *short-distance-flying*.

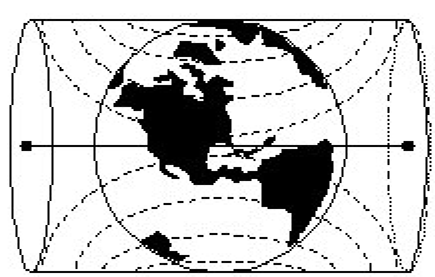


Figure-2.7 Transverse Mercator projection *[K6-2]*

2.3 International NAV Standards

For the sake of uniformity of the air NAV, international bodies have formed standards.

www.faa.gov www.icao.int www.iata.org

www.tc.gc.ca

www.arinc.com www.fcc.gov www.itu.int

Figure-2.8 Logo of national and international bodies

- **International Civil Aviation Organization (ICAO):** It is a UN organization that has the following responsibilities:

  1) Develop standards for aviation matters.
  2) Recommend specific systems[7].
  3) Provides international agreements for ATC.
  4) Defines country airspace. That is which country has responsibility over the ocean, etc.

- **International Air Transport Association (IATA):** Represents the interest of commercial airlines.

- **International Telecommunication Union (ITU):** Recommends all allocations of frequencies in the radio spectrum.

- **National Aviation:** ICAO, IATA, and ITU work closely with national bodies such as:

  1) *Canada:*
     - ❖ Transport Canada Civil Aviation (TCCA)
     - ❖ Industry Canada

[7] But not a specific Hardware (HW).

2) *United States*:
   - ❖ Federal Aviation Administration (FAA)
   - ❖ Federal Communication Commission (FCC)
   - ❖ Aeronautical Radio Inc. (ARINC): Private association for US-airlines; however, since the US dominate the world airline business ARINC standards are used worldwide.

2.4 Airspace Structure

For effective and safe ATC, the airspace is organized according to its specific purpose and use. The sky is divided into *Controlled Airspace* [Classes A, B, C, D, & E] and *Uncontrolled Airspace* [Class G].

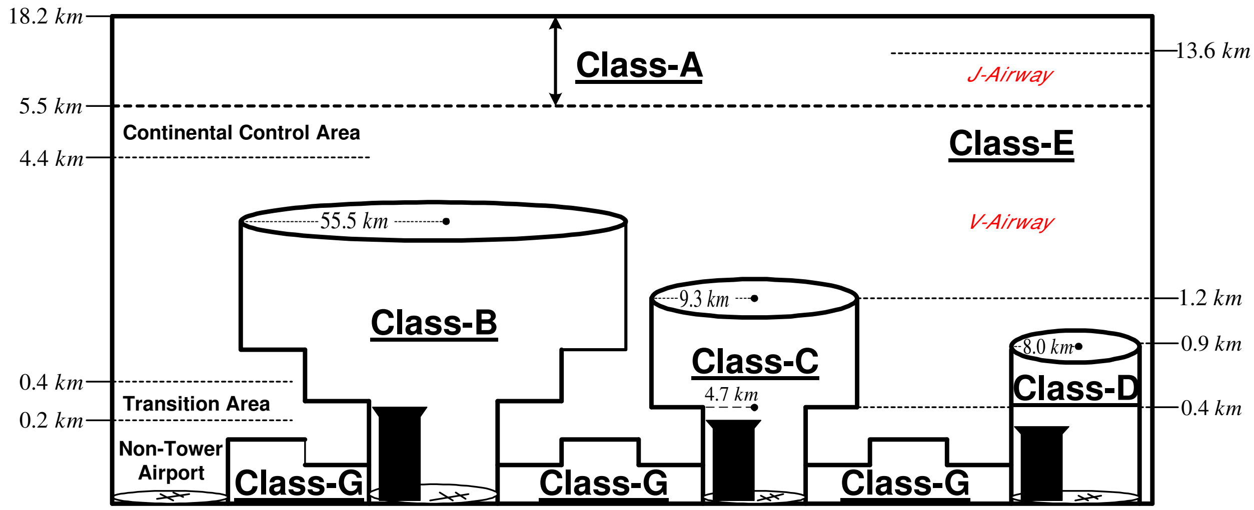


Figure-2.9 Airspace structure for Canada and the US as of 1991 *[K6-3]*

- <u>**Some Definitions:**</u>

1) *Mean Sea Level (MSL):* Represents the Altitude (ALT) above the earth surface w.r.t sea.
2) *Above Ground Level (AGL):* Represents the ALT above the earth surface w.r.t GND.
3) *Flight Level (FL)*
4) *Statue Mile (sm)*

$$\text{ft MSL} > \text{ft AGL} \tag{2.6}$$

$$\text{FL1} \equiv 100 \text{ ft MSL} \tag{2.7}$$

$$1 \text{ sm} = 0.869 \text{ nm} = 1.609 \text{ km} \tag{2.8}$$

- <u>**Class *A*: Positive Control Area (PCA):**</u>

1) ***ABOVE*** all airspaces.
2) From *FL180 to FL600*.
3) A/C is controlled with Instrument Flight Rules (IFR).
4) Radio communication with ATC before entering this zone is required.

- **Class *B*: Terminal Control Area (TCA):**

    1) Airspace in the vicinity of major busy airports in ***BIG*** cities.
    2) Lightweight airplanes cannot fly here (special permission from ATC may be granted).
    3) Uppermost circle radius = *30 nm = 55.5 km*.
    4) Maximum airspeed = *250 kts*.
    5) A/C must have a 2-way VHF radio and a mode-C transponder.
    6) IFR aircrafts must have VOR equipment.
    7) Visual Flight Rules (VFR) corridors are sometimes designated.
    8) Radio communication with ATC before entering this zone is required.

- **Class *C*: Airport Radar Service Area (ARSA):**

    1) Airspace is similar to class B but for smaller ***CITIES***.
    2) Lightweight airplanes cannot fly here (special permission from ATC may be granted).
    3) Control tower is equipped with radar.
    4) Uppermost circle radius = *5 nm = 9.3 km*.
    5) Maximum airspeed = *250 kts*.
    6) A/C must have a 2-way VHF radio and a mode-C transponder.
    7) Radio communication with ATC before entering this zone is required.

- **Class *D*: Airport Traffic Area (ATA):**

    1) Airspace in the vicinity of very small or ***DIMINUTIVE*** airports.
    2) Lightweight airplanes may fly here (unless specified otherwise).
    3) Control tower may not be equipped with radar.
    4) Circle radius = *5 sm = 4.4 nm = 8.0 km*.
    5) Maximum airspeed = *250 kts*.
    6) A/C must have a 2-way VHF radio and a mode-C transponder.
    7) Radio communication with ATC before entering this zone is required.

- **Class *E*: Contains Remaining Controlled Airspaces:**

    1) This airspace is ***EVERYWHERE*** due to its vast volume.
    2) Lightweight airplanes may fly here (unless specified otherwise).
    3) Airspace categories:

        ❖ *Continental Control Area:* From *FL145 to FL180* (Bottom of Class A).

        ❖ *Transition Area:* Transition between *Airport* and *En-route* environment. From *700 ft AGL to 1200 ft AGL.*

        ❖ *Non-Tower Airport Area:* Communication with ATC is recommended.

- **Class *G*: Completely Uncontrolled Airspace:**

1) Low flying ***GND*** airspace.
2) Lightweight airplanes may fly here freely.
3) ATC does not have authority for traffic control.

Airspace Class	Communications with ATC for Entry	Separation Provided	Minimum Qualifications
A	Required	All A/C	Instrument Rating
B	Required	All A/C	Private or Student Certificate dependent on location
C	Required	VFR from IFR	Student Certificate
D	Required	Runway Operations	Student Certificate
E	Not Required for VFR	None for VFR	Student Certificate
G	Not Required	None	Student Certificate

Figure-2.10 Airspace summary *[K6-3]*

- **Special Use Airspace:**

1) *Warning Area (W):* Area outside territorial limits (e.g. Over international water).
2) *Alert Area (A):* Area with high volume of aerial activity (e.g. Pilot training).
3) *Prohibited Area (P):* Flight is prohibited for security reasons (e.g. White House).
4) *Restricted Area (R):* Flight is restricted for safety reasons (e.g. Area where guns are used).
5) *MIL Operations Area (MOA):* Separate Civilian (CIV) traffic from MIL training activities.
6) *MIL Training Route (MTR):* Low amplitude/high speed MIL flight training.
7) *Air Defense Identification Zone (ADIZ):* Area where identification (ID) is required for national security reasons. If A/C does not respond it may be shot.

- **Oceanic Control Areas:**

1) Airspace over ocean, outside individual countries.
2) Airspace is similar to class A.
3) Traffic control is the responsibilities of adjacent countries identified by ICAO[8].

- **Airway:**

1) It is a highway in the sky.
2) Directions to fly along this highway are given by signal radiation of VOR or VORTAC GND stations.

[8] As an example, the Caribbean area is under US responsibility.

3) *Airway width = 10 sm = 16 km.*
4) Airway types:

- *V-Airway:*
  - Synonyms: *V* or *VOR* or *Victor Airway*.
  - Located in class E airspace (till *FL180*).
  - For short-trip / low ALT flights.
  - Used by IFR and VFR A/C.

- *J-Airway:*
  - Synonyms: *J* or *Jet* or *Juliet Airway*.
  - Located in class A airspace (From *FL180 to FL450*).
  - For long-trip / high ALT flights.
  - Used by IFR A/C.

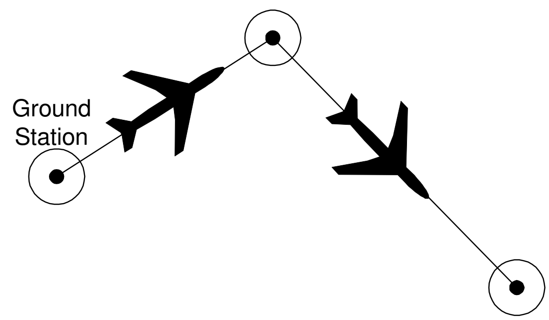


Figure-2.11 *V*- or *J*-Airway NAV (i.e. without using waypoints)

2.5 Air Traffic Control System

The purpose of ATC is to promote safety and order in the sky. Also, ATC system is similar worldwide due to ICAO standardization.

- **<u>ATC achieves its duties by managing and manipulating the following:</u>**

1) *Systems:*
   - A/C.
   - Airport systems.
   - NAV systems.
   - Traffic control devices.
   - GND equipments.
   - Etc.

2) *Information:*
   - Apply rules and procedures.
   - Provide weather information.
   - Enable communication with aircrafts.
   - Etc.

- **ATC complexity are due to:**

    1) *Traffic density*
    2) *Weather conditions*
    3) *Cost considerations*
    4) *Available technology*

- **ATC facilities include:**

    1) *Air Traffic Control Tower Center (ATCTC):* Handles traffic around the airport.
        - ❖ GND Control

    2) *Terminal Radar Approach Control (TRACON):* Handles traffic in the terminal area.
        - ❖ Departure control
        - ❖ Approach control

    3) *Air Route Traffic Control Center (ARTCC):* Handles En-route traffic.
        - ❖ En-route Control

    4) *Flight Service Station (FSS):*
        - ❖ Flight planning.
        - ❖ Traffic condition bulletins.
        - ❖ Weather information.
        - ❖ Status of Navigational Aid (NAVAID) reports.
        - ❖ Handling certain non-tower airport traffic.
        - ❖ Communication with VFR flights.
        - ❖ Coordination of search operations.

- **MIL ATC:**

    1) MIL ATC works closely with CIV ATC.

    2) MIL ATC facilities include:
        - ❖ *Radar Approach Control Facility (RAPCON):* US Air Force.
        - ❖ *Radar Air Traffic Control Center (RATCC):* US Navy.

2.5.1 Visual Flight Rule – VFR

- **Definition:** VFR is based on flying by visually looking out of the cockpit to navigate with reference to GND landmarks and to avoid collisions with other A/Cs.

- **VFR A/C can voluntarily access various ATC services:**

    1) *Radar traffic information service*
    2) *Radar assistance*: Obtain NAV vectors.
    3) *Terminal radar service*: Merging of VFR and IFR traffic.
    4) *Tower En-route control*: Short VFR flights.

- **VFR Flight Plan:** In general, filling a flight plan is not required for VFR A/C; however it is a good practice since it could be useful in search and rescue operations in case an accident or a problem occurs. If a flight plan is filled, we do not need to follow it fully, but if we do it would be better. Canadian authorities are more strict than the US and requires that we fill-in a flight plan.

- **VFR Weather Minima:**

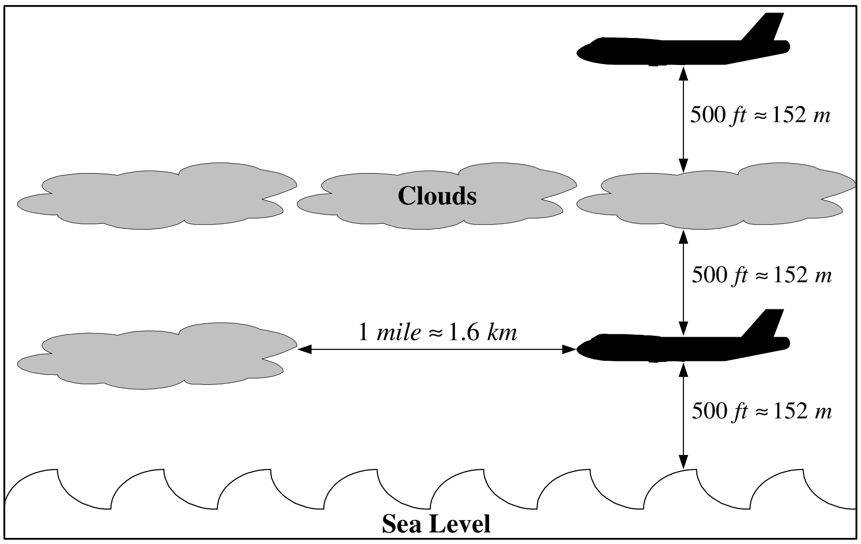


Figure-2.12 VFR weather minima for Canada and the US *[K3-3]*

2.5.2 Instrument Flight Rule – IFR

- **Definition:** IFR is based on flying using airborne instruments (not by looking out of the cockpit).

- **Characteristics of IFR Flights:**

  1) Pilot must have certain qualifications.
  2) Pilot and A/C equipment are subject to periodic certification checks.
  3) A/C must be equipped with:
     - Gyroscope
     - Navigational equipments
     - Radio communication
     - Radar transponder
     - Etc.

- **ATC control of IFR traffic is based on 2 methods:**

  1) *Procedural Method:* ATC uses real-time position information received from the A/C as it flies over predetermined GND *reporting points* (e.g. VOR stations).

2) *Radar Method:* ATC uses continuous position information obtained from *GND based radars*. This method is more precise; therefore, closer A/C separation distances are possible.

Figure-2.13 Radar method enables small separation distances

- **IFR Traffic Separation:**

1) ATC performs traffic separation for IFR A/C only (not VFR).
2) IFR separation is highly dependent on:
   - ❖ ALT
   - ❖ A/C speed.
   - ❖ Airborne NAV equipment used.
   - ❖ Control method used (Procedural or Radar).
   - ❖ Etc.

- **IFR Flight Phases:**

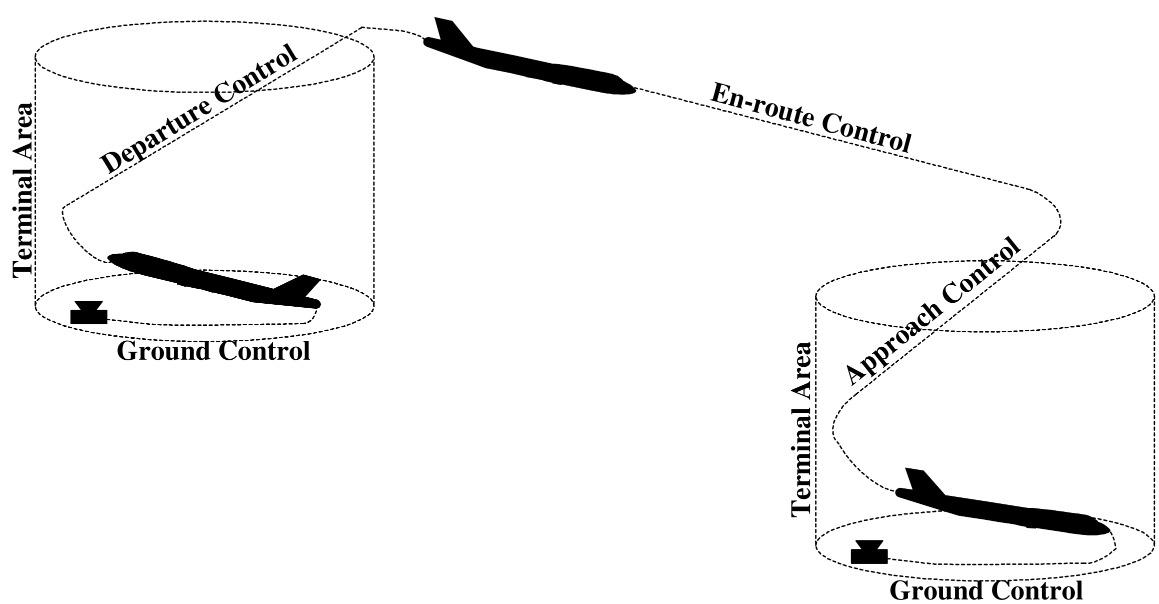


Figure-2.14 IFR flight phases *[K3-4]*

1) *Departure:*
   - Pilot communicates with *Clearance Delivery*.
   - Departure transponder code is assigned.
   - Transfer to *GND Control* for taxi clearance to the active runway.
   - Transfer to *Tower Control* when A/C is ready to takeoff.
   - Transfer to *Departure Control* when A/C is airborne until the end of *Terminal Area*.

2) *En-route:*
   - Transfer to *En-route Control* during transition airspace.
   - As the flight proceeds the A/C is handed-over from one ARTCC to another.
   - Pilots are required to follow their routes & ALT, and report their position.
   - Change of route may be requested dues to weather or other circumstances.
   - While flying over the ocean, the rules and regulations of ICAO and the country controlling the airspace must be followed[9].

3) *Arrival and Landing:*
   - Before arriving to the airport, ARTCC contacts *Approach Control*.

   - Transfer to *Approach Control* is done in 2 methods:
     - *Holding Fix Method:* Use when the sky is busy.
     - *Radar ID Method:* Transfer is done in a predetermined area.

   - Transfer to *Tower Control* when A/C is ready to land using ILS. Also at this stage, VFR A/C which land visually are mixed with IFR airplanes; therefore, *first come first serve* principle is applied.

   - Transfer to *GND Control* for taxi clearance to the active gate.

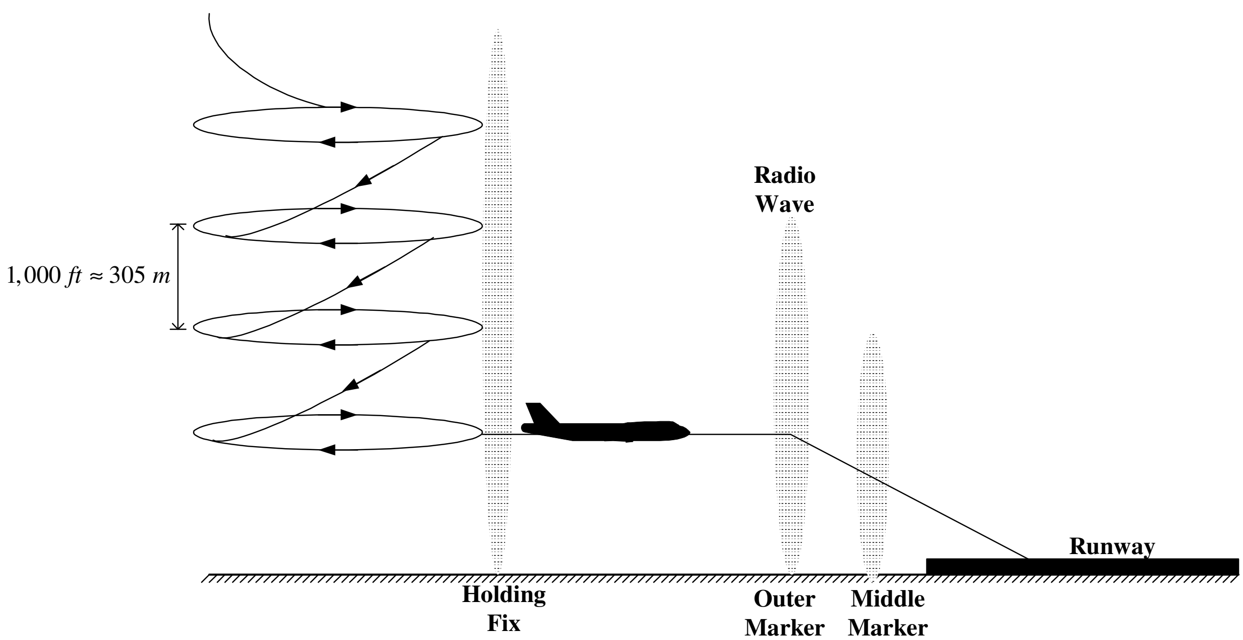


Figure-2.15 Holding fix method and ILS for the landing phase ***[K3-5]***

[9] As an example, North Atlantic permits only IFR fights.

2.5.3 VFR and IFR

- **Flight Planning:** A flight plan is prepared filled either in person, by telephone, or by radio with FSS.

    1) A/C ID (registration sign).
    2) Type of flight plan (VFR or IFR).
    3) A/C NAV equipments.
    4) Route of flight (V or J-Airway).
    5) Departure point.
    6) Destination point.
    7) Departure time (in GMT).
    8) *En-route* estimated time.
    9) Fuel onboard (in terms of endurance time).
    10) Cruising ALT (for IFR you request the ALT).
    11) True airspeed (kts).
    12) Number onboard (crew + passengers).
    13) Color of A/C.
    14) Alternate airport (mandatory for IFR).
    15) Remarks as necessary.
    16) Pilot's Info: *Name / License # / Address / Telephone #*

- **Cruising ALT:** Specific cruising ALT must be respected depending on the A/C HDG.

IFR

$000^0 \rightarrow 179^0$	$180^0 \rightarrow 359^0$
FL30 ≈ **0.914 km**	*FL20* ≈ **0.610 km**
FL50 ≈ **1.52 km**	*FL40* ≈ **1.22 km**
FL70 ≈ **2.13 km**	*FL60* ≈ **1.83 km**
FL90 ≈ **2.74 km**	*FL80* ≈ **2.44 km**
FL110 ≈ **3.35 km**	*FL100* ≈ **3.05 km**
FL130 ≈ **3.96 km**	*FL120* ≈ **3.66 km**
FL150 ≈ **4.57 km**	*FL140* ≈ **4.27 km**
FL170 ≈ **5.18 km**	*FL160* ≈ **4.88 km**
FL190 ≈ **5.79 km**	*FL180* ≈ **5.49 km**
FL210 ≈ **6.40 km**	*FL200* ≈ **6.10 km**
FL230 ≈ **7.01 km**	*FL220* ≈ **6.71 km**
FL250 ≈ **7.62 km**	*FL240* ≈ **7.32 km**
FL270 ≈ **8.23 km**	*FL260* ≈ **7.93 km**
FL290 ≈ **8.84 km**	*FL280* ≈ **8.53 km**
FL330 ≈ **10.06 km**	*FL310* ≈ **9.45 km**
FL370 ≈ **11.28 km**	*FL350* ≈ **10.67 km**
FL410 ≈ **12.50 km**	*FL390* ≈ **11.89 km**
Etc	*Etc*

VFR

$000^0 \rightarrow 179^0$	$180^0 \rightarrow 359^0$
FL35 ≈ **1.07 km**	*FL25* ≈ **0.762 km**
FL55 ≈ **1.68 km**	*FL45* ≈ **1.37 km**
FL75 ≈ **2.29 km**	*FL65* ≈ **1.98 km**
FL95 ≈ **2.90 km**	*FL85* ≈ **2.59 km**
FL115 ≈ **3.51 km**	*FL105* ≈ **3.20 km**
FL135 ≈ **4.12 km**	*FL125* ≈ **3.81 km**
FL155 ≈ **4.72 km**	*FL145* ≈ **4.42 km**
FL175 ≈ **5.33 km**	*FL165* ≈ **5.03 km**
FL195 ≈ **5.94 km**	*FL185* ≈ **5.64 km**
FL215 ≈ **6.55 km**	*FL205* ≈ **6.25 km**
FL235 ≈ **7.16 km**	*FL225* ≈ **6.86 km**
Etc	*Etc*

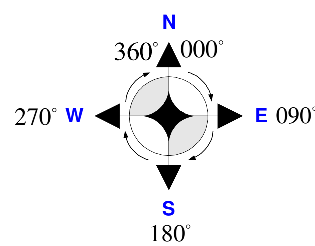


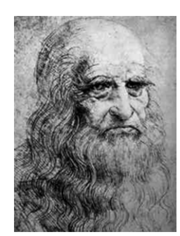
Figure-2.16 VFR and IFR cruising ALTs ***[K6-4]***

Chapter 3

Early NAV

No human investigation can claim to be scientific if it doesn't pass the test of mathematical proof.

— Leonardo Da Vinci



3.1 Flight Controls

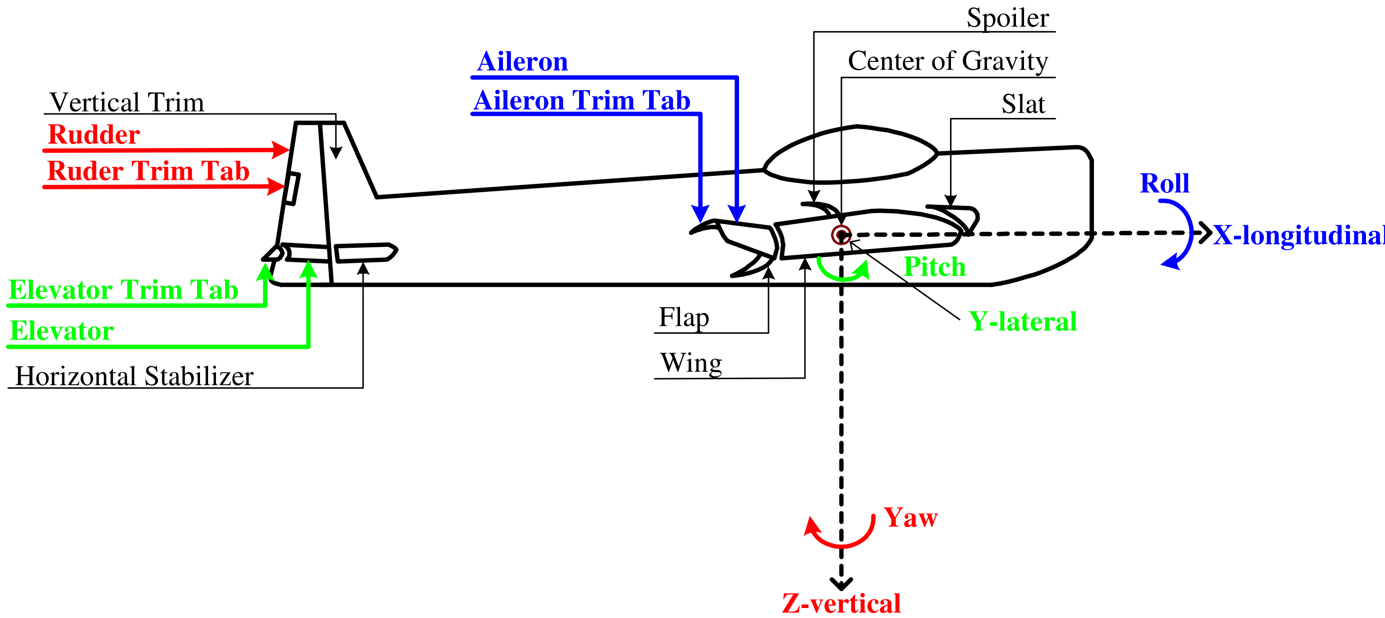


Figure-3.1 A/C control surfaces *[K1-1]*

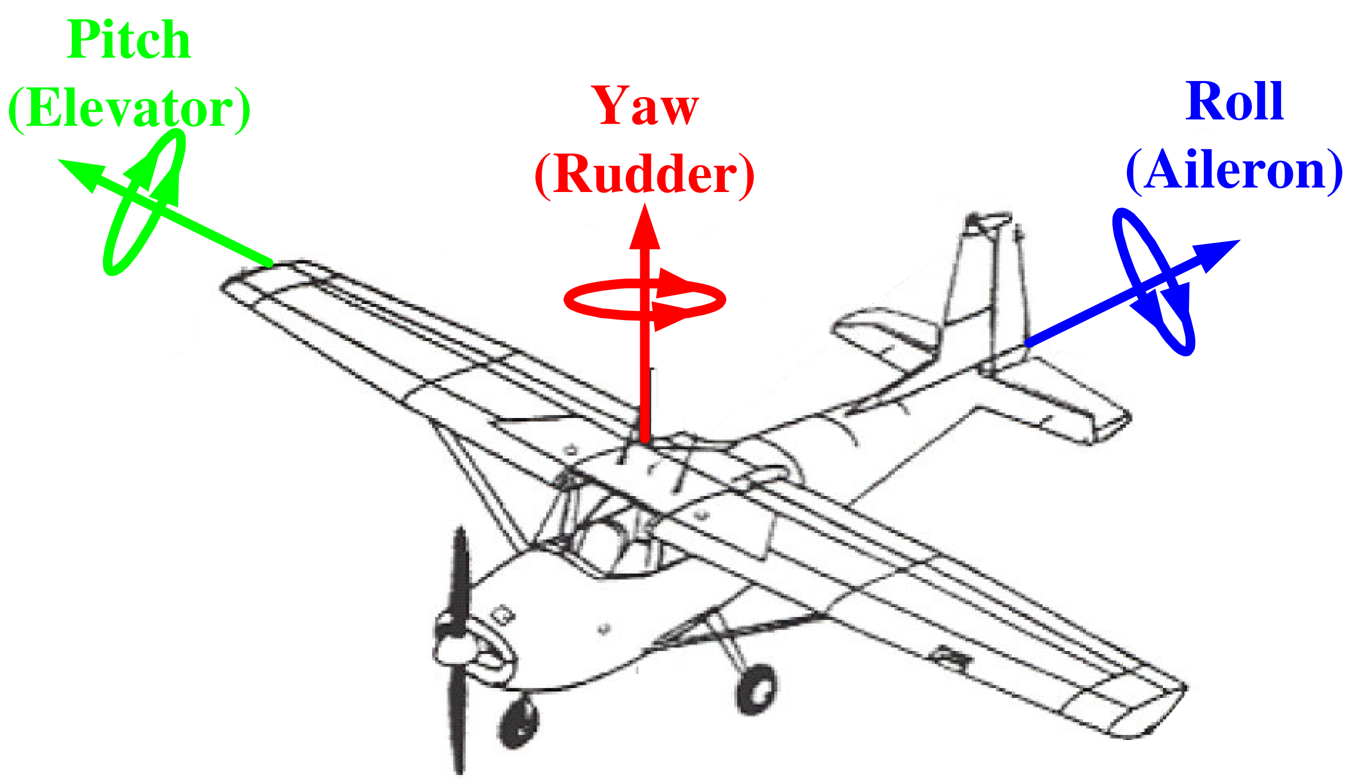


Figure-3.2 A/C 6-degrees of freedom *[K2-1]*

- **<u>Movement Control:</u>** 6 degrees of freedom.

  1) *Roll:* Rotation movement of an A/C about a *longitudinal axis (X)*.
     - ❖ Hardware: *Aileron*.
     - ❖ Control: *Lateral* motion of the *stick*.

  2) *Pitch:* Rotation movement of an A/C about a *lateral axis (Y)*.
     - ❖ Hardware: *Elevator*.
     - ❖ Control: *Longitudinal* motion of the *stick*.

  3) *Yaw:* Rotation movement of an A/C about a *vertical* axis (*Z*).
     - ❖ Hardware: *Rudder*.
     - ❖ Control: *Rudder pedals*.

- **<u>Lift and Drag:</u>** Affects the A/C movement in the *X* and *Z axes*.

  - ❖ Hardware:
    - ➢ Flaps
    - ➢ Slats
    - ➢ Spoilers

- **<u>Thrust:</u>** That is the driving force of the A/C is accomplished by the power-plant control.

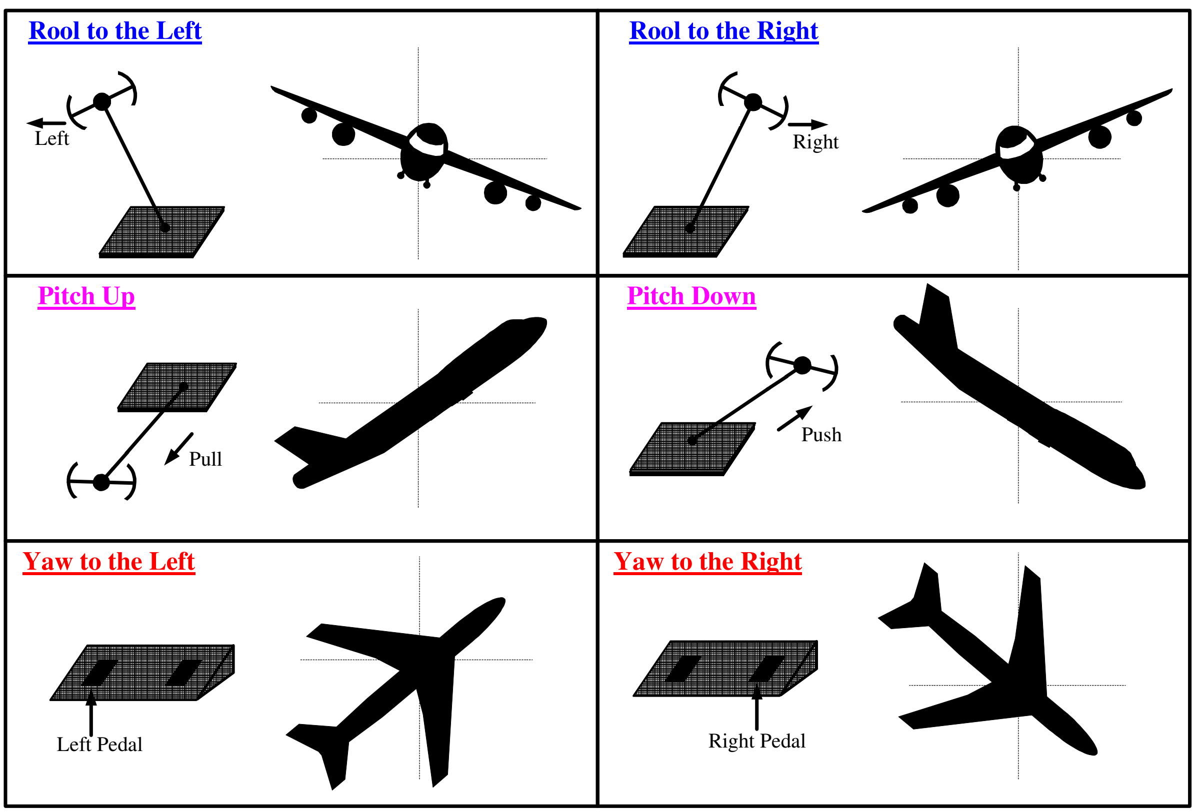


Figure-3.3 Controlling A/C 6-degrees of freedom

3.2 Basics of Flight Instruments

The purpose of A/C instruments are to provide the pilot with critical information for safe and effective operation of the vehicle.

- **Basic-Six or Basic-T:**

    1) *Pitot Static Instruments:* 1, 2, 3
    2) *Attitude Instruments:* 4, 5
    3) *HDG Instruments:* 6, 7

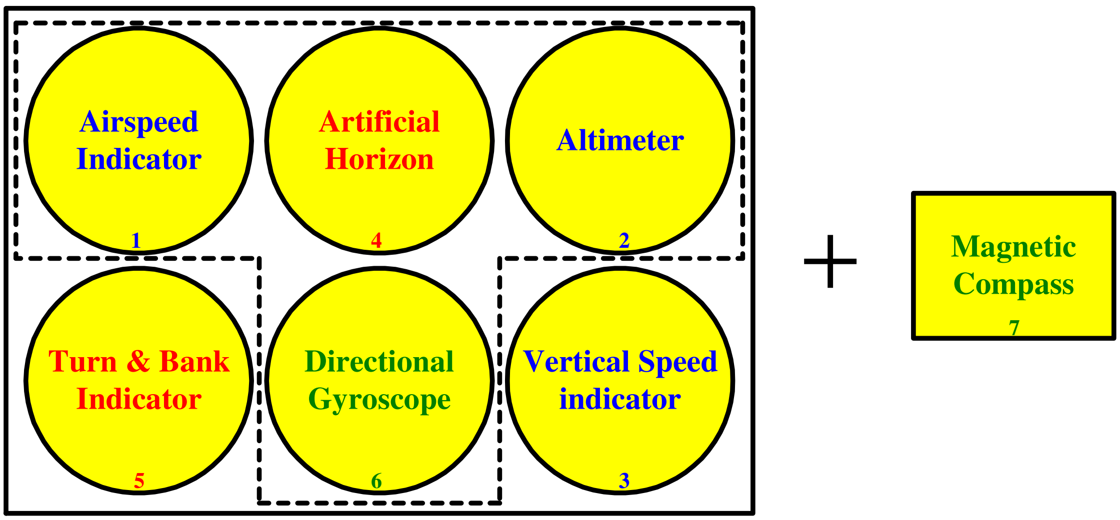


Figure-3.4 Basic flight instruments ***[K6-5]***

3.2.1 Pitot Static Instruments

- **Preliminary Concept:**

    1) *Pitot Static Instrument System:* Device driven by static pressure and pitot pressure obtained from the pitot static tube.

    2) *Pitot Static Tube:* It is an open-ended tube where moving fluid flows in order to measure the stagnation pressure. Pitot static tube is mounted under the wing.

    3) *Bernoulli Equation at Constant Elevation:* Assuming ideal uncompressible fluid.

$$P_d = \frac{\rho V^2}{2} \tag{3.1}$$

$$P_t = P_s + P_d \tag{3.2}$$

V : Speed.

ρ : Air density.

P_s : Static pressure.

P_d : Dynamic pressure.

P_t : Pitot or total or stagnation pressure.

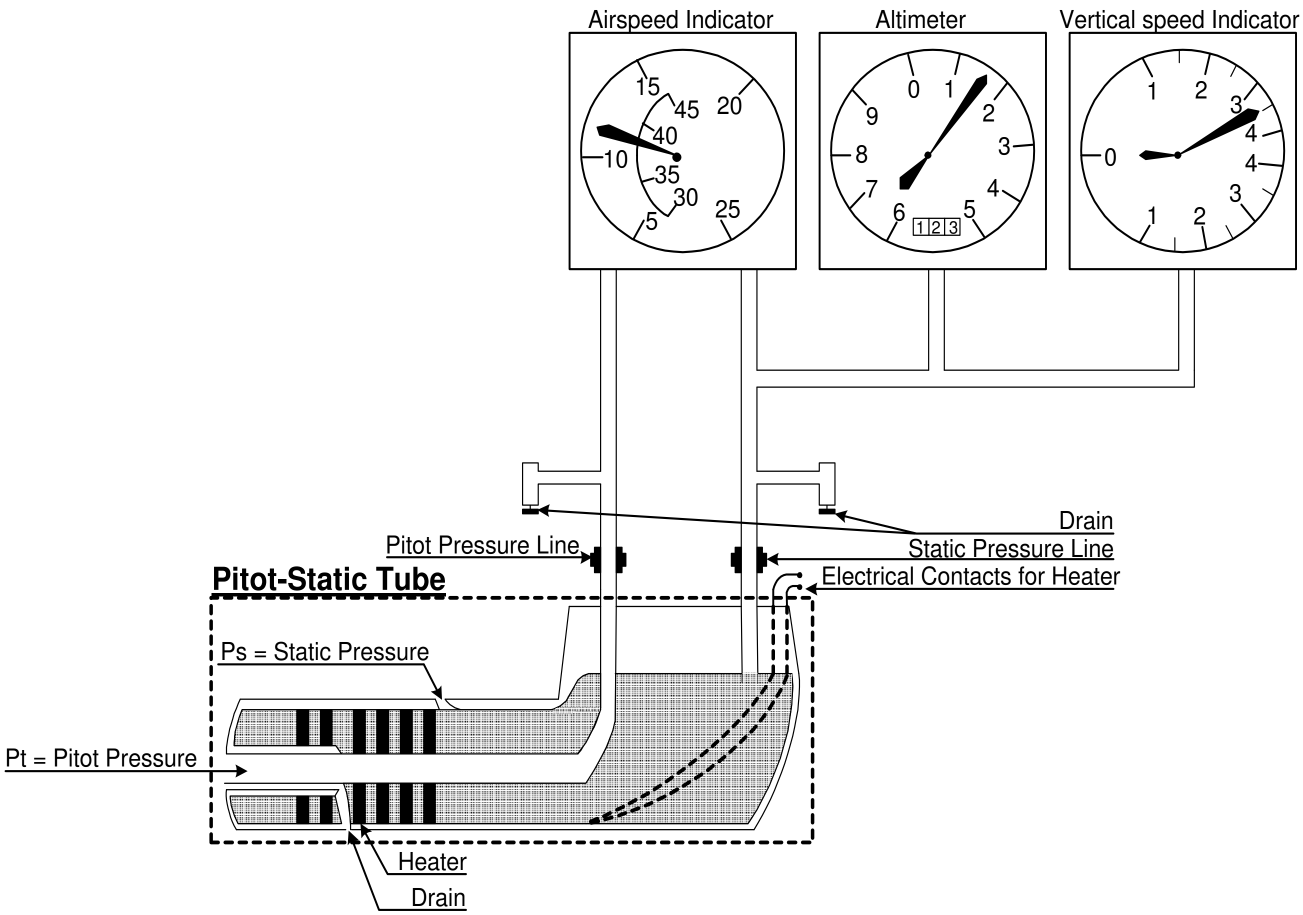


Figure-3.5 Pitot static instrument system *[K3-6]*

- **Useful Equations:**

1) *Equation of state for perfect gases:*

$$P = \rho R T \tag{3.3}$$

$$\text{K}^\circ = 273.16 + {}^\circ\text{C} \tag{3.4}$$

P : Pressure $\left[\text{Pa}\right]$.

T : Temperature $\left[\text{K}^\circ\right]$.

R : 287.05 $\left[\text{m}^2 / \text{s}^2\text{K}^\circ\right]$.

ρ : Atmospheric Air density $\left[\text{kg} / \text{m}^3\right]$.

2) *Sea Level Values:* Measured on a standard day in Mediterranean referred to as Standard ICAO.

Temperature:	$T_0 = 15\ ^\circ\mathrm{C} = 59\ ^\circ\mathrm{F} = 288.16\ \mathrm{K}^\circ$
Speed of Sound:	$a_0 = 340.0\ \left[\mathrm{m}/\mathrm{s}\right] = 1116.2\ \left[\mathrm{ft}/\mathrm{s}\right]$
Density:	$\rho_0 = 1.225\ \left[\mathrm{kg}/\mathrm{m}^3\right] = 0.002377\ \left[\mathrm{slug}/\mathrm{ft}^3\right]$
Pressure:	$P_0 = 1\ [\mathrm{atm}] = 101{,}325\ [\mathrm{Pa}] = 1013.25\ [\mathrm{mbar}] = 29.92\ [\mathrm{in\ Hg}]$

(3.5)

3) *Equations:* Takeoff and landing are extremely related to pressure. As a result, flights are mostly in early morning or at night since temperature is low at that time.

$$\downarrow \text{Temperature} \quad \therefore \quad \uparrow \text{Pressure} \quad \therefore \quad \uparrow \text{Speed} \quad \therefore \quad \downarrow \text{ALT} \tag{3.6}$$

[10]

Speed of Sound:	$\left(\frac{a}{a_0}\right) = \left(\frac{T_{st}}{T_0}\right)^{0.5}$
Density:	$\left(\frac{\rho}{\rho_0}\right) = \left(\frac{T_{st}}{T_0}\right)^{4.25}$
Pressure:	$\left(\frac{P}{P_0}\right) = \left(\frac{T_{st}}{T_0}\right)^{5.25}$
Viscosity:	$\left(\frac{\mu}{\mu_0}\right) = \frac{T_{st}^{1.5}(T_0 + 120)}{T_0(T_{st} + 120)}$

$\leftarrow$ Temperature $[\mathrm{K}^\circ]$ (3.7)

$$H = \frac{(T_{st} - T_0)}{\Delta} \tag{3.8}$$

$\nearrow$ $\left\{ \begin{array}{l} \text{Altitude } [\mathrm{m}] \\ \text{Temperature } [\mathrm{K}^\circ] \\ \Delta = \Delta_{kelvin} = -0.0065 \left[\mathrm{K}^\circ/\mathrm{m}\right] \end{array} \right\}$

OR

$\searrow$ $\left\{ \begin{array}{l} \text{Altitude } [\mathrm{ft}] \\ \text{Temperature } [^\circ\mathrm{C}] \\ \Delta = \Delta_{celsius} = -0.00198 \left[^\circ\mathrm{C}/\mathrm{ft}\right] \end{array} \right\}$

[10] The relation between ALT and temperature is not at all times linear and proportional, and the best proof for that are the two layers of atmosphere known as the troposphere and the mesosphere. For more on ALT, temperature, pressure w.r.t. the atmosphere refer to Appendix C.

4) *Several Definitions of ALT:*

- H_a = *Absolute ALT*: Height above earth surface.
- H_t = *True ALT*: Height above sea level but with Standard ICAO values.
- H_d = *Density ALT*: Height above sea level with ambient density.

$$H_d = \text{Height Above Sea Level}\Big|_{\rho=\text{actual ambient density (i.e. now)}} \tag{3.9}$$

- H_p = *Pressure ALT*: Height above sea level with ambient pressure.

$$H_p = \text{Height Above Sea Level}\Big|_{P=\text{actual ambient pressure (i.e. now)}} \tag{3.10}$$

- *Standard ICAO*: The ambient pressure and density are always less than the Standard ICAO ones.

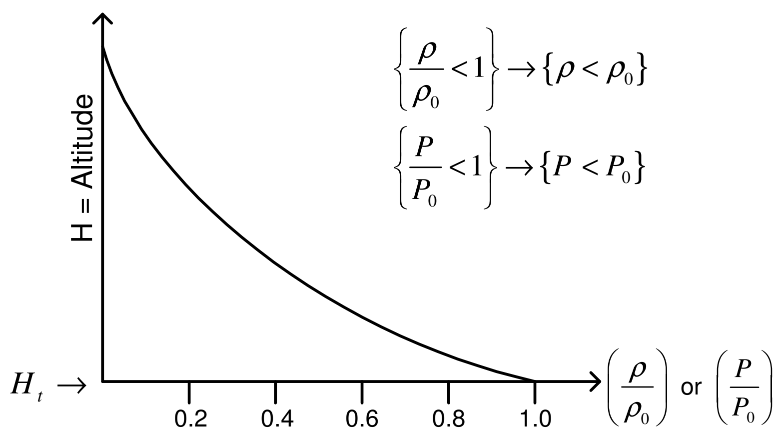


Figure-3.6 Height versus pressure or density

$$\left\{\begin{array}{l} H_d \big|_{\rho=\rho_0} = H_t \\ H_p \big|_{P=P_0} = H_t \end{array}\right\} \rightarrow \therefore \text{ @ Standard ICAO: } \{H_t = H_d = H_P\} \tag{3.11}$$

$$\left\{\begin{array}{l} H_d \big|_{\rho\neq\rho_0} > H_t \\ H_p \big|_{P\neq P_0} > H_t \end{array}\right\} \tag{3.12}$$

- **Airspeed Indicator (AI):** To obtain the speed we measure the difference between the pitot and the static pressure, i.e. we obtain the dynamic pressure.

$$\left\{P_d = P_t - P_s = \frac{\rho V^2}{2}\right\} \rightarrow \left\{V = \sqrt{\frac{2P_d}{\rho}}\right\} \tag{3.13}$$

1) *Indicated Airspeed (IAS):* Uncorrected speed.

2) *Calibrated Airspeed (CAS):* Airspeed corrected for instrument error and pitot static system error.

3) *Equivalent Airspeed (EAS):* Airspeed corrected for compressibility error. This error is negligible up to *250 kts* and *10,000 ft ≈ 3.05 km*.

4) *True Airspeed (TAS):* Airspeed corrected for air density error.

$$TAS = CAS\sqrt{\frac{\rho_0}{\rho}} \tag{3.14}$$

- **Altimeter:** It is a barometer that measures the change in pressure ALT, and outputs the elevation height. Altimeter[11] could be set to different pressure modes for a specific ALT reading:

1) *Pressure at Nautical Height (QNH):*
    - ❖ Pressure Type: Sea level pressure.
    - ❖ Used for:
        - ➢ Takeoff
        - ➢ Landing
        - ➢ VFR Flying

2) *Pressure at Standard Sea Level (QNE):*
    - ❖ Pressure Type: Standard sea level pressure (i.e. *1 atm*).
    - ❖ Used for:
        - ➢ High ALT flying.
        - ➢ Unpopulated area flying.

3) *Pressure at Field Elevation (QFE):*
    - ❖ Pressure Type: Airfield pressure.
    - ❖ Used for:
        - ➢ Aerobatic flying.

[11] To avoid traffic conflict and to ensure security in the sky, the same altimeter setting should be used for a given region.

- **Vertical Speed Indicator (VSI):** It measures the change in pressure ALT and outputs the vertical speed. If the A/C flies straight, the pressure is constant and hence, VSI is set to zero.

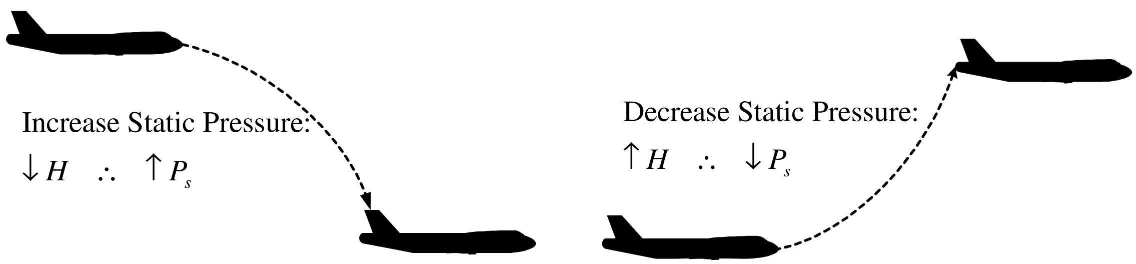


Figure-3.7 Static pressure variation with vertical motion

3.2.2 Attitude Instruments

These instruments are based on using a gyroscope[12] to indicate the roll and pitch of an A/C.

- **Artificial Horizon:** A gyro operated instrument that shows the *roll X-axis* and *pitch Y-axis* attitudes of an A/C w.r.t. an artificial reference line horizon of earth. The gyro spins on the *yaw Z-axis*. Also, the gyro can be driven either by vacuum air turbine or electric motor.

- **Turn and Bank Indicator:** A gyro-operated instrument that is driven either by vacuum air turbine or electric motor. This was the first gyro that made blind flying possible. This instrument contains 2 independent mechanisms:

1) *Gyro driven pointer:* This pointer indicates the rate of turn of the A/C.

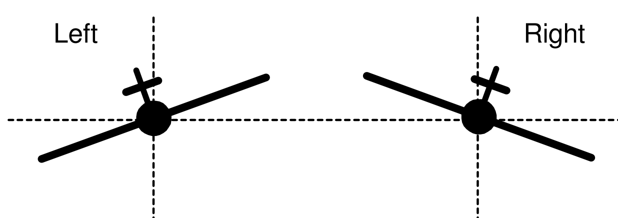


Figure-3.8 Rate of turn of the A/C

[12] Gyroscope or Gyro is a rotating device that will maintain its original plane of rotation no matter which direction the A/C is turned.

2) *Detect slip and skid in the turn:* There is a ball placed in a fluid filled curve-tube in the turn and bank indicator. If we travel straight the ball stays in the middle. To make a turn in a stable way, we must turn while making sure that the ball remains in the middle. This means that *g* and *centrifugal acceleration* are perpendicular.

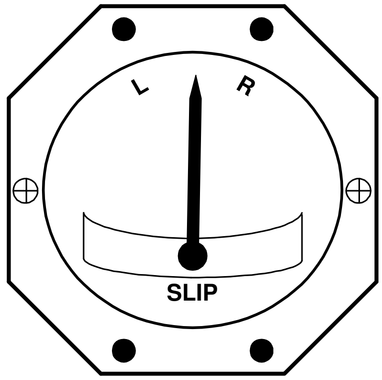


Figure-3.9 Turn and bank indicator *[K6-6]*

3.2.3 HDG Instruments

These instruments are used to indicate the A/C HDG.

- **Directional Gyroscope (DG):** This instrument displays the A/C *yaw* angle. The gyro rotates about the *pitch Y-axis* and it is suspended in *2D Y-Z-axis*. The gyro can be driven either by vacuum air turbine or electric motor.

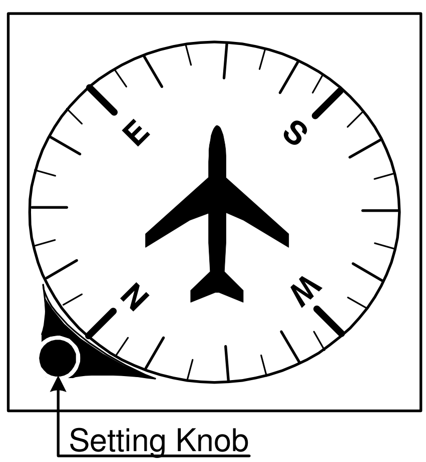


Figure-3.10 Directional gyroscope indicator *[K6-7]*

1) The HDG can be set by the setting knob.

2) DG should be reset every 10 to 15 minutes (modern DGs reset automatically).

3) DG error are caused by:
   - ❖ Earth rotation (15^0 / hr).
   - ❖ Turn, Bank, and Pitch.
   - ❖ Gyro bearing friction.

- **Magnetic Compass:** This instrument displays the A/C horizontal direction or HDG w.r.t. earth magnetic meridian. Today, the compass principle is applied in modern navigational displays as: Radio Magnetic Indicator (RMI) and Horizontal Situation Indicator (HSI)[13]. Magnetic Compass errors are:

1) *Static Error:* Magnetic pole and the true geographical pole are not at the same location. A compass always points to the magnetic north pole, hence a *static error*.

   - ❖ Magnetic pole rotates slowly around the true pole (1 rev. / 1000 years).
   - ❖ Magnetic variation: Difference between the true and magnetic HDG.
   - ❖ In Montréal:
     - ➢ Magnetic variation = 15^0 W.
     - ➢ This means that the magnetic North is 15^0 to the West of the true North.
     - ➢ True HDG of magnetic north = 360 – 15 = 345^0.

2) *Dynamic Error:* Magnetic meridian has important dips in high LAT because after all earth is not spherical; therefore, the compass card deviates from its horizontal position; hence, the Center of Gravity (CG) changes, resulting in *dynamic error*. If an A/C is traveling say to the East; when the plane:

   - ❖ *Accelerate*: the compass display the HDG but more tilted to the North.
   - ❖ *Decelerate*: the compass display the HDG but more tilted to the South.

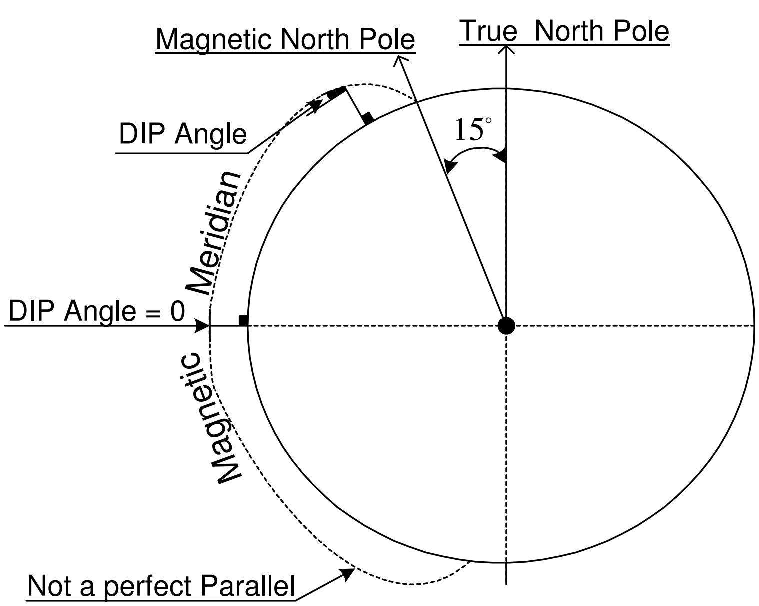


Figure-3.11 Earth Magnetic field *[K6-8]*

[13] RMI and HSI will be discussed further in Chapter 5.

3) *Deviation Error:* Airplanes are constructed in general from metals[14] (i.e. aluminum alloy) which could potentially be affected by the earth magnetic field and/or airborne avionics; therefore, an electromagnetic (EM) field will be generated, hence *deviation error*.

- ❖ *Adjustable magnets:* are used to compensate the deviation error.
- ❖ *Compass swinging:* should be performed annually to the compass to correct the deviation error.

	N			E			S			W		
True HDG	**000^0 / 360^0**	**030^0**	**060^0**	**090^0**	**120^0**	**150^0**	**180^0**	**210^0**	**240^0**	**270^0**	**300^0**	**330^0**
Displayed HDG	003^0	031^0	061^0	090^0	122^0	147^0	179^0	209^0	241^0	270^0	298^0	334^0
Deviation Error	- 3^0	- 1^0	- 1^0	0^0	- 2^0	+ 3^0	+ 1^0	+ 1^0	- 1^0	0^0	+ 2^0	- 4^0

Figure-3.12 Compass deviation error *[K3-7]*

3.3 Pilotage and Dead Reckoning

- **Preliminary Concept:**

1) *True Airspeed (TAS):* Airspeed w.r.t. air.

2) *HDG:* Angle between A/C longitudinal axis and the meridian axis, measured clockwise from the meridian (i.e. from North). HDG is used in correspondence with TAS.

3) *Ground Speed (GS):* Airspeed w.r.t. GND.

4) *TK:* Angle between GS vector and the meridian axis, measured clockwise from the meridian (i.e. from North). TK is used in correspondence with GS.

5) *Wind:* It is determined by its speed or Wind Speed (WS) and direction or Wind Angle (WA).

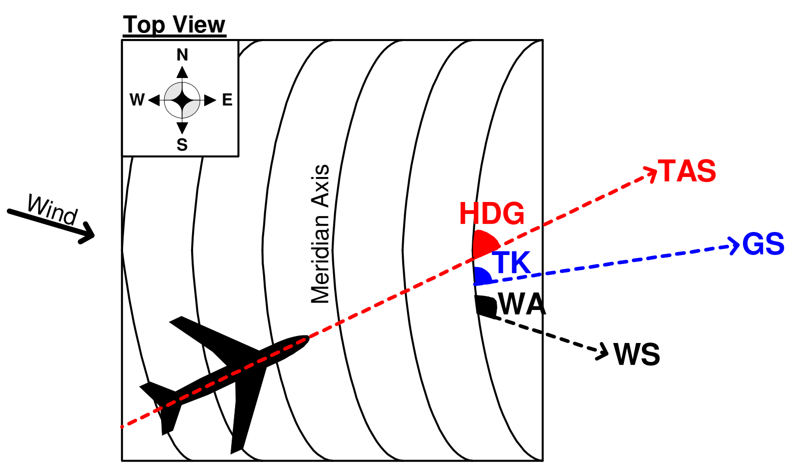


Figure-3.13 Definition of speed vectors

[14] Recently a lot of Research and Development (R&D) efforts are underway to adapt the use of composite materials instead of the traditional aluminum alloy core. The major disadvantage of this transformation is the high cost of composite materials.

6) *Drift Angle (δ):* Angle measured by going from the HDG to the TK.

7) *Bearing:* Angle of an object seen from the A/C measured clockwise from the meridian (i.e. from North).

- **Going from *A* to *B*:**

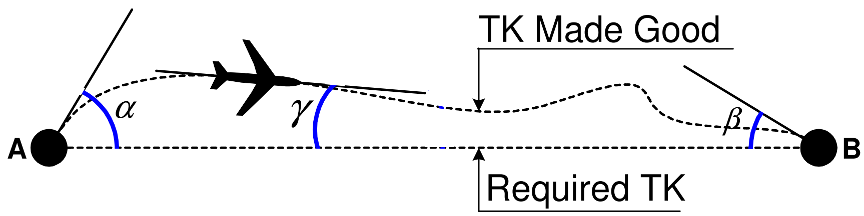


Figure-3.14 Distinction between Required TK and TK Made Good *[K3-8]*

1) *Required TK:* Angle representing the proposed A/C path over GND.
2) *TK Made Good:* Angle representing the actual A/C path over GND.
3) *Opening Angle (α):* Angle representing the departure *TK Error*.
4) *Closing Angle (β):* Angle representing the destination *TK Error*.
5) *TK Error (γ):* Angle representing the difference between the *Required TK* and *TK Made Good*.

- **10^0 Drift Lines:**

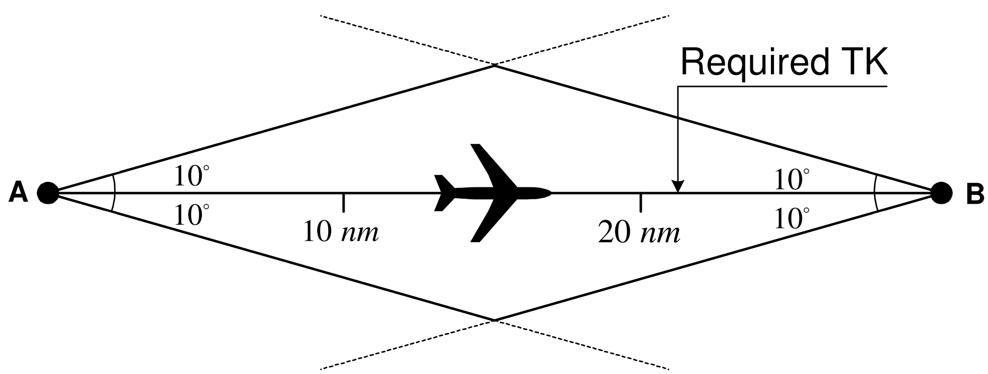


Figure-3.15 10^0 Drift Lines *[K3-9]*

1) *10^0 Drift Lines* are drawn around the *Required TK* to help:
   - *NAV*
   - *Estimate wind drift*

2) *10^0 nm* marks are identified along the *Required TK* to help the estimate of *GS*.

3) It is recommended to perform a *GS* check every *10 nm*.

- **<u>Double TK Error Method:</u>**

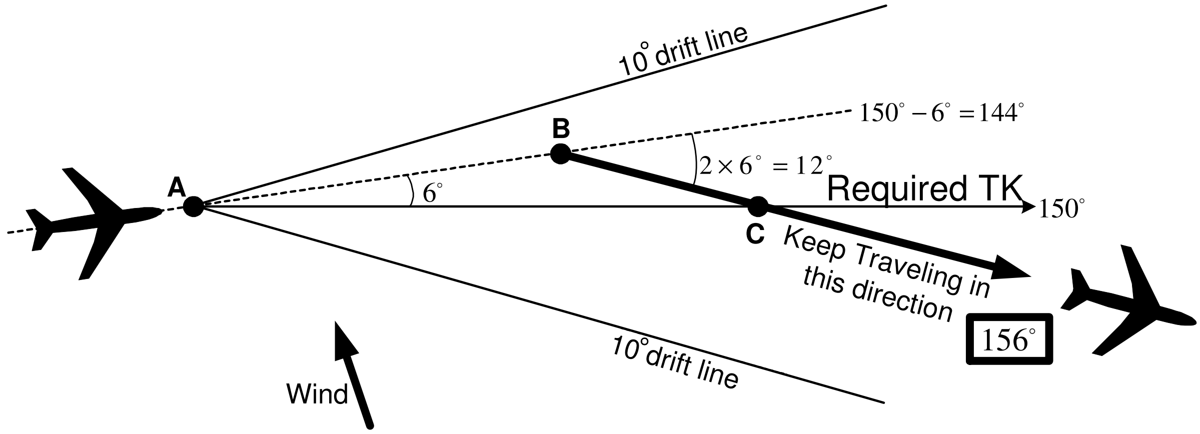


Figure-3.16 Double TK Error Method *[K3-10]*

1) Method is used to regain *Required TK*.

2) Due to crosswinds we deviate from the *Required TK* by say 6^0.

3) To regain the *Required TK* we travel in the opposite direction by 2×6^0. The first 6^0 is to get back to the *Required TK*, and the next 6^0 is to compensate for future crosswinds.

4) The time it takes to fly from *A* to *B* to *C* is approximately the same time it takes to fly from *A* to *C*.

- **<u>Visual TK Alteration Method:</u>**

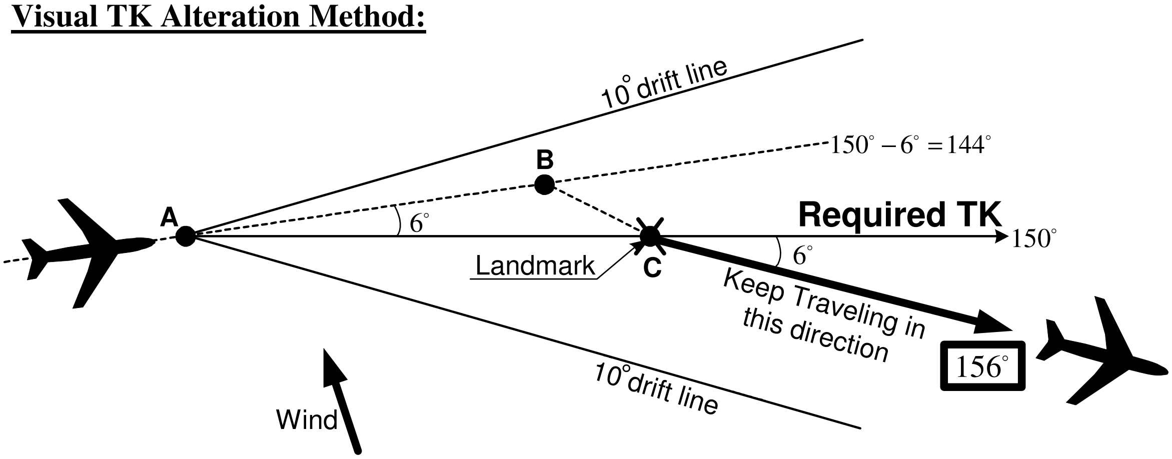


Figure-3.17 Visual TK Alteration Method *[K3-10]*

1) Method is used to regain *Required TK* based on finding a landmark.
2) Due to crosswinds we deviate from the *Required TK* by say 6^0.
3) We locate a landmark on the *Required TK* (*C*) and fly toward it.
4) At the *Required TK*, we go south by 6^0 to overcome future crosswinds.

- **Two Point Visual Range Method:**

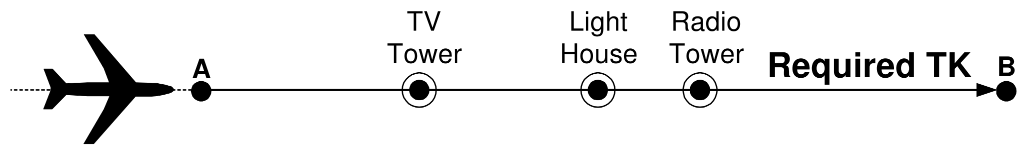


Figure-3.18 Two Point Visual Range Method

1) Method is used to fly on the *Required TK* through visual reference to landmarks.
2) Locate a landmark on the *Required TK* and fly toward it.
3) Repeat this procedure until destination is reached.

- **Opening/Closing Angles Method:**

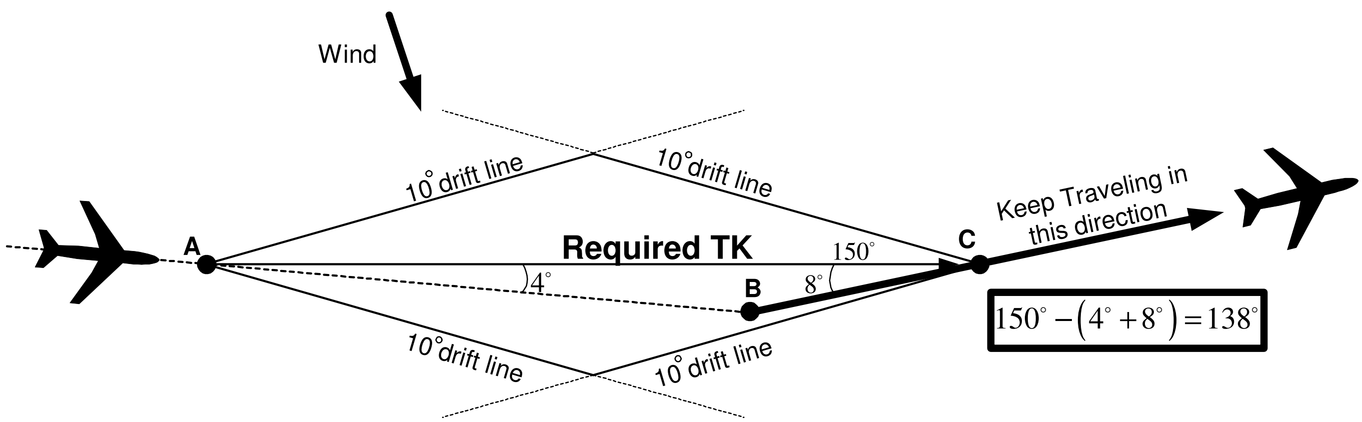


Figure-3.19 Opening/Closing Angles Method *[K3-11]*

1) Method is used if we determine late in the travel that we are off the *Required TK*.
2) Due to crosswinds we deviate from the *Required TK* by say 4^0.
3) Late in the travel at point *B* we estimate the *Opening Angle* (4^0) and the *Closing Angle* (8^0).
4) To reach *C* we travel in the opposite direction by $4^0 + 8^0$.

- **Return to Point of Departure Method:**

1) Method is used if we suddenly detect a problem during NAV and want to turn back.

2) Main reasons to use this method are:
   - *Weather conditions*
   - *Mechanical problems*
   - *Etc.*

3) Estimate *GS*, determine the *TK* angle, and calculate δ.

4) Calculate the *Reciprocal TK*.

$$\text{Reciprocal TK} = \text{TK} \pm 180^0 \quad (3.15)$$

5) Finally obtain the *Reciprocal HDG*

$$\text{Reciprocal HDG} = \text{Reciprocal TK} + \delta \tag{3.16}$$

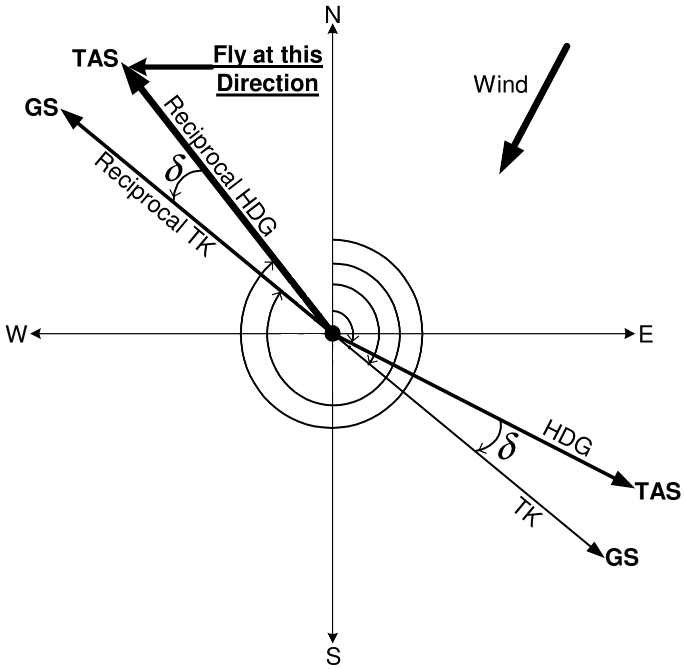


Figure-3.20 Return to Point of Departure Method

- **Triangulation Method:**

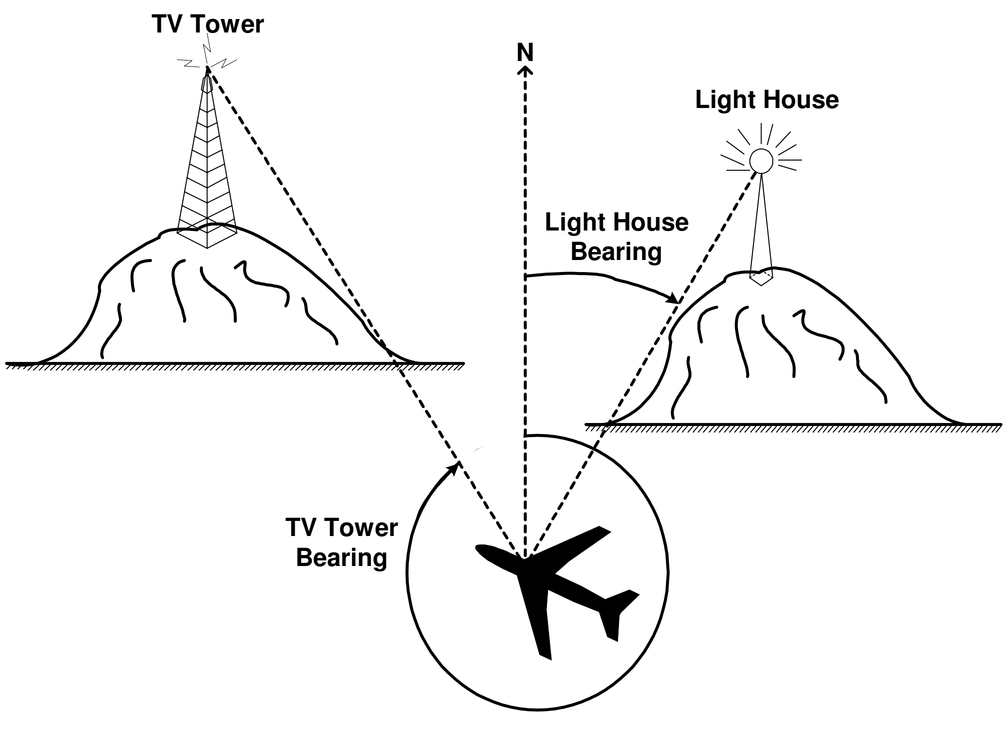


Figure-3.21 Triangulation Method ***[K1-2]***

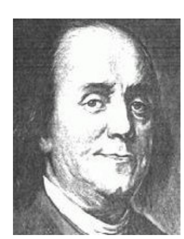
1) Method is used to determine the A/C position.
2) We identify 2 or more landmarks and determine their bearings.
3) We then extend their lines.
4) The point where the lines intersect is where the aircraft is located.

Chapter 4

Air Communication

The man who does things makes many
mistakes, but he never makes
the biggest mistake of all
— doing nothing.

— Benjamin Franklin



4.1 Radio Wave Propagation

- **Definition:**

1) *On Earth:* There exist 2 method of propagation: *GND Wave* and *Sky Wave*.

2) *In Free-Space:* Propagation occurs in straight line or *Line Of Sight (LOS) Wave*.

3) *Ionosphere Layer*[15]*:* A region of the earth atmosphere containing gas molecules that absorbs incoming solar radiation of X-ray[16] frequencies and above to reach earth.

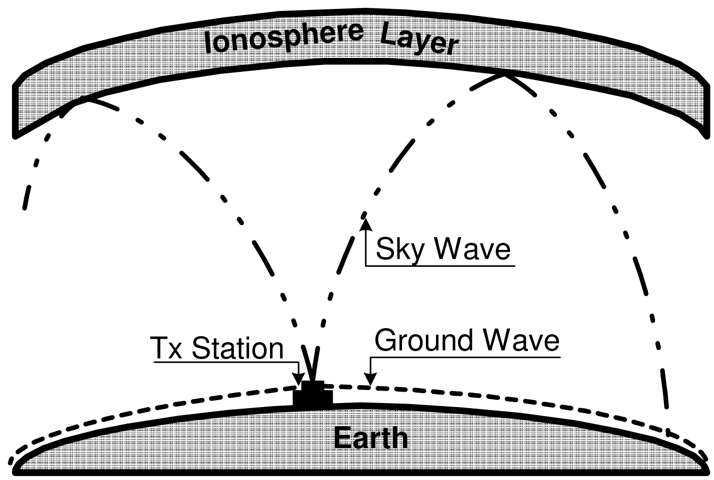


Figure-4.1 GND and sky wave propagation ***[K6-9]***

4.1.1 GND Wave

- **Frequency:** *0 to 3 MHz* (Covers the following bands: ELF, SLF, ULF, VLF, LF, and MF)

- **Wave Characteristics:**

1) *Wave Location:* The signal is in proximity to the earth surface.

2) *At Lower Frequencies (ELF, SLF, ULF, VLF, and LF):*
   - ❖ *Propagation velocity ≠ constant*
   - ❖ Interference may occur due to atmospheric noise
   - ❖ Provided sufficient Tx power is available: *Max Range ≈ 5,000 miles ≈ 8,000 km*
   - ❖ Optimum antenna size: $height \approx half\ wavelength = \lambda / 2 = velocity / (2 \times frequency)$

3) *At Higher Frequencies (MF):*
   - ❖ The power received is smaller than the power transmitted; therefore we obtain a larger attenuation factor.

[15] For more on the atmosphere layers refer to Apendix C.
[16] X-ray bandwidth varies from: $3x10^7$ to $3x10^9$ GHz.

BAND	MEANING	FREQUENCY	WAVE	
ELF	Extremely Low Frequency	3 --- 30 Hz	GND Wave	Sky Wave
SLF	Super Low Frequency	30 --- 300 Hz		
ULF	Ultra Low Frequency	300 --- 3000 Hz		
VLF	Very Low Frequency	3 --- 30 kHz		
LF	Low Frequency	30 --- 300 kHz		
MF	Medium Frequency	300 --- 3000 kHz		
HF	High Frequency	3 --- 30 MHz	N/A	
VHF	Very High Frequency	30 --- 300 MHz		LOS Wave
UHF	Ultra High Frequency	300 --- 3000 MHz		
SHF	Super High Frequency	3 --- 30 GHz		
EHF	Extremely High Frequency	30 --- 300 GHz		

Figure-4.2 Frequency band classification *[K6-10]*

$$[W_R]_{\text{Ground wave}} \propto \frac{1}{L^4} \tag{4.1}$$

$$\alpha = 10\log_{10}\left(\frac{W_R}{W_T}\right) \tag{4.2}$$

α : Signal attenuation [dB].

W_R : Power received [Watts].

W_T : Power transmitted [Watts].

L : Distance between Tx and Rx.

Frequency	Over Sea-Water		Over Earth	
kHz	100 miles dB	1,000 miles dB	100 miles dB	1,000 miles dB
150	- 40	- 88	- 45	- 105
300	- 40	- 99	- 51	....
500	- 40	- 108	- 65	....
1,000	- 42	- 125	- 82	....
2,000	- 44	....	- 99	....
5,000	- 47	....	- 117	....

$100\ miles \approx 161\ km$

$1{,}000\ miles \approx 1{,}610\ km$

Figure-4.3 GND wave signal attenuation *[K3-12]*

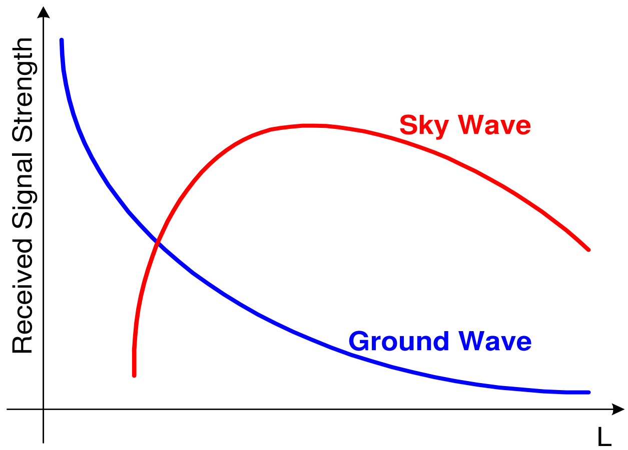


Figure-4.4 Received signal power versus "*L*" *[K1-3]*

4.1.2 Sky Wave

- **Frequency:** *0 to 30 MHz* (Covers the following bands: ELF, SLF, ULF, VLF, LF, MF, and HF)

- **Wave Characteristics:**

1) *Wave Location:* The signal is in the sky based on the reflective property of the ionosphere layer.

2) *During Nighttime:*
   - ❖ Ionosphere layer is closer to the earth surface.
   - ❖ Sky wave travel at a flatter angle.
   - ❖ *Advantage:* Larger signal distances.
   - ❖ *Disadvantage:* More skip zones with no reception will exist.

3) *During Daytime:*
   - ❖ Ionosphere layer is farther away from the earth surface.
   - ❖ Sky wave travel with an angle.
   - ❖ *Disadvantage:* Smaller signal distances.
   - ❖ *Advantage:* Less skip zones with no reception will exist.

$$[W_R]_{\text{Sky wave}} \propto L \tag{4.3}$$

4.1.3 LOS Wave

- **Frequency:** *30 to 300,000 MHz* (Covers the following bands: VHF, UHF, SHF, and EHF)

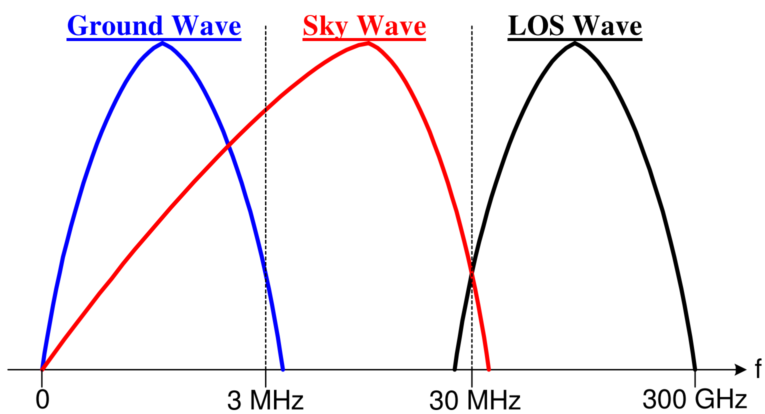


Figure-4.5 Frequency bandwidth for GND, sky, and LOS waves

- **Wave Characteristics:**

1) *LOS wave travels in a straight line.*
2) *Propagation follows the laws of free-space.*
3) *Propagation velocity = constant = speed of light = c =* 3×10^8 *[m/s]*
4) *In the VHF band the LOS signal may be affected by the reflection of various objects on earth.*

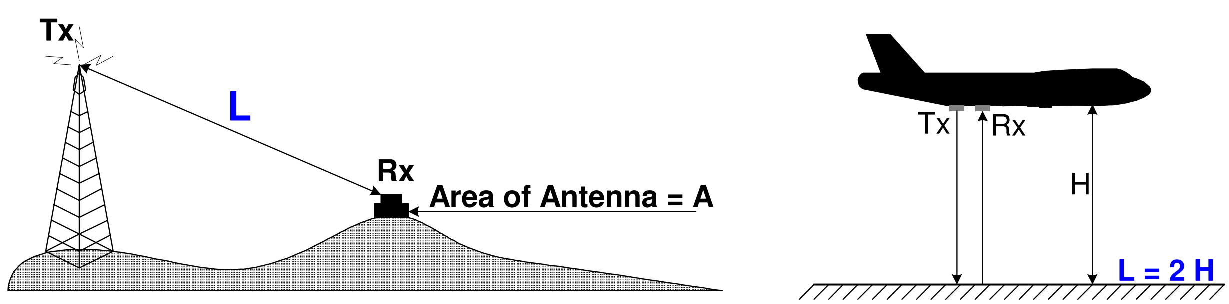


Figure-4.6 Graphical definition of "*L*"

$$\left[\frac{W_R}{W_T}\right]_{\text{LOS wave}} = \frac{\text{Area of Antenna}}{\text{Sphere Area}} = \frac{A}{4\pi L^2} \qquad (4.4)$$

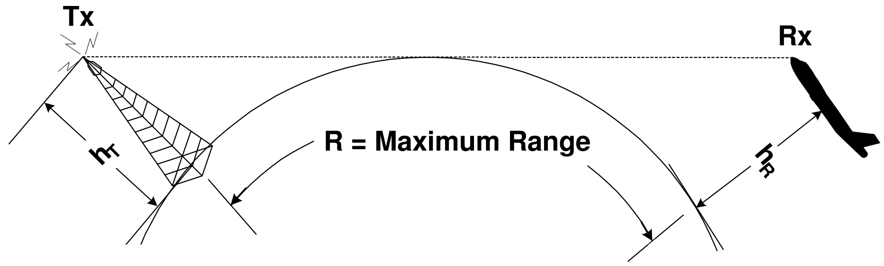


Figure-4.7 Maximum LOS range due to earth curvature *[K6-11]*

$$R = 1.2\left(\sqrt{h_T} + \sqrt{h_R}\right) \tag{4.5}$$

R : Maximum LOS Range [nm].

h_R : Height of Rx [ft].

h_T : Height of Tx [ft].

Frequency	Over Sea-Water		Over Earth	
	100 miles dB	1,000 miles dB	100 miles dB	1,000 miles dB
All Frequencies	- 40	- 60	- 40	- 60

$100\ miles \approx 161\ km$

$1{,}000\ miles \approx 1{,}610\ km$

Figure-4.8 LOS wave signal attenuation *[K3-12]*

- **Atmospheric Conditions:** Signal attenuation becomes more important at the SHF and the EHF band due to the effect of rain and fog.

RAIN

Loss dB/m	Heavy Rain (16 mm/hr) GHz	Moderate Rain (4 mm/hr) GHz	Light Rain (1 mm/hr) GHz	Drizzle (0.25 mm/hr) GHz
10^{-3}	15	37	100	....
10^{-4}	7	12	20	43
10^{-5}	3	6	9	20
10^{-6}	....	3	4	8
10^{-7}	....	....	....	4

FOG

Loss dB/m	Visible Distance 100 ft GHz	200 ft GHz	500 ft GHz	1,000 ft GHz
10^{-3}	20	......	......	......
10^{-4}	7	12	20	......
10^{-5}	......	4	7	12
10^{-6}	......	......	......	3

$100\ ft \approx 30.5\ m$

$200\ f \approx 61\ m$

$500\ ft \approx 152\ m$

$1{,}000\ ft \approx 305\ m$

Figure-4.9 LOS wave signal attenuation due to atmospheric conditions *[K1-4]*

4.2 Communications

- **Speech Signal:** There are 2 ways to send a speech waveform:

  1) *Amplitude Modulation (AM):* Amplitude of the carrier signal varies

     ❖ Frequency band: *MF ≈ 540 – 1800 kHz*

     ❖ Aviation radio technology is based on AM.

  2) *Frequency Modulation (FM):* Frequency of the carrier signal varies.

     ❖ Frequency band: *VHF ≈ 88 – 108 MHz*

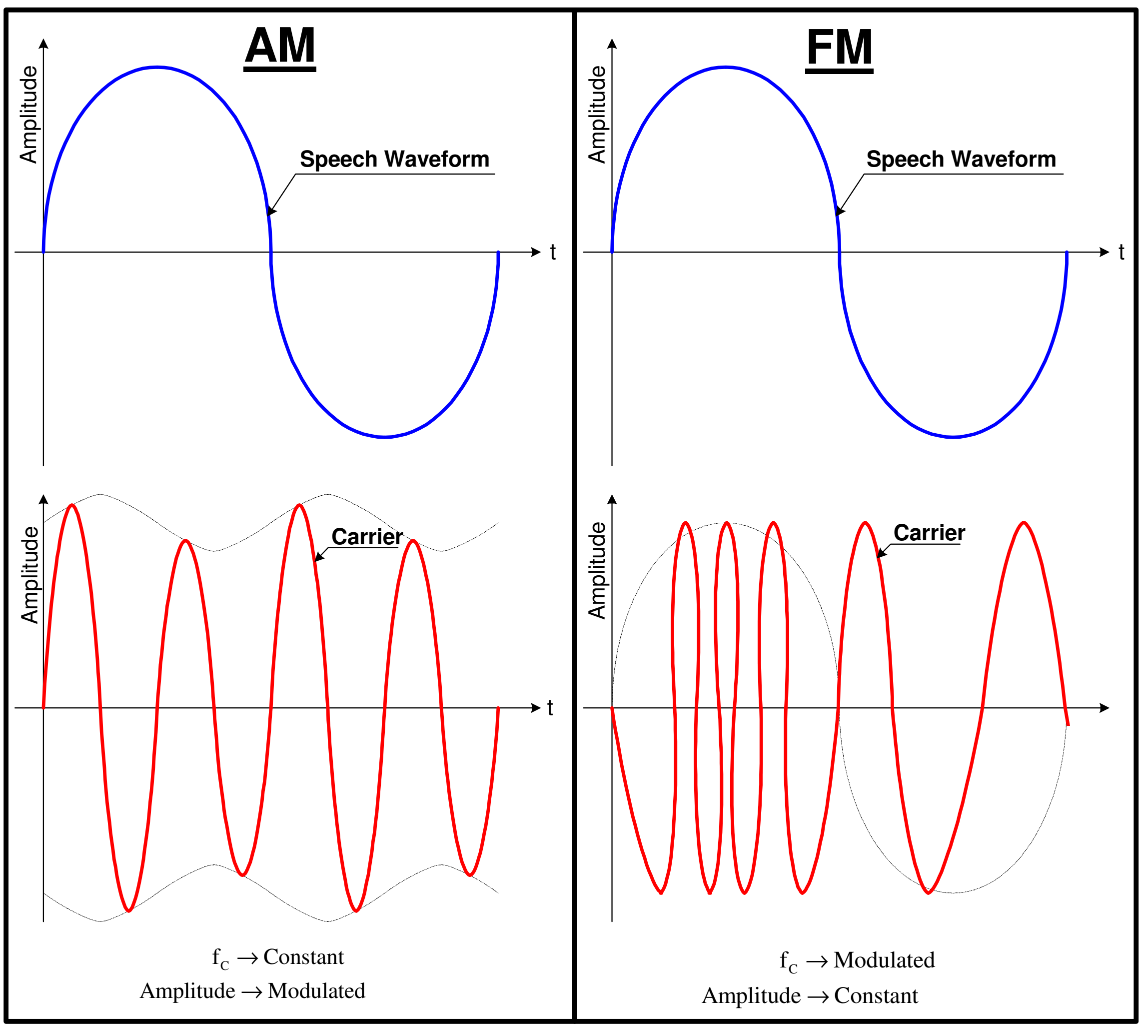


Figure-4.10 AM and FM modulation techniques ***[K6-12]***

- **Headset:** Used for radio communications.
    1) *Interface:* Transponder
    2) *Microphones:* Noise canceling
    3) *Headphones:* Use a noise sensor or a phase reversing circuitry to attenuate noise.
    4) *Activation:* Press on the *push-to-talk* button to start transmission.

Figure-4.11 Noise canceling headset[17] ***[K4-2]***

[17] The price of this headset is roughly $600 US.

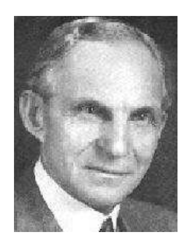
Part II
Avionics

Chapter 5

Short-Range NAVAIDS

Anyone who stops learning is old, whether at twenty or eighty. Anyone who keeps learning stays young.

— Henry Ford



5.1 Automatic Direction Finder – ADF

- **Principle:** Provides A/C bearing w.r.t. a GND station known as Non Directional Beacon (NDB). The bearing is measured clockwise starting from the A/C longitudinal axis and stopping at the segment of the A/C – NDB. Note that the reading obtained in the Flight Compartment (F/C) indicator is a relative[18] bearing known as the ADF bearing. To obtain the NDB magnetic bearing we need to perform the following:

$$\{\text{NDB Magnetic Bearing w.r.t. A/C}\} = \{\text{A/C Magnetic HDG}\} + \{\text{ADF Relative Bearing}\} \quad (5.1)$$

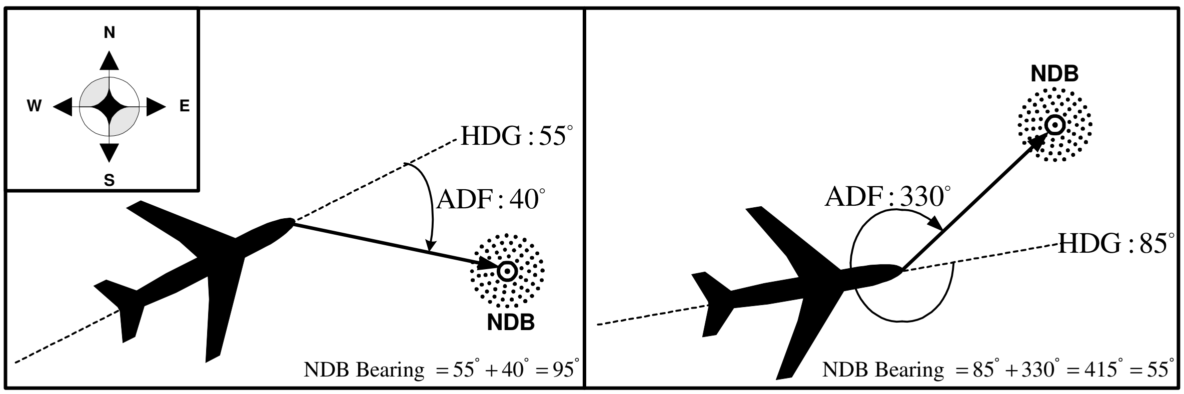


Figure-5.1 Examples illustrating the ADF principle *[K6-13]*

- **Applications:**

  1) *TK Intercept: To be able to get back to the TK due to crosswind.*

  2) *Station Homing: Travel toward or away from an NDB.*

     ❖ Wrong Station Homing:
       ➢ *ADF bearing is aligned to the A/C longitudinal axis; therefore a dramatic curve will occur due to crosswind.*

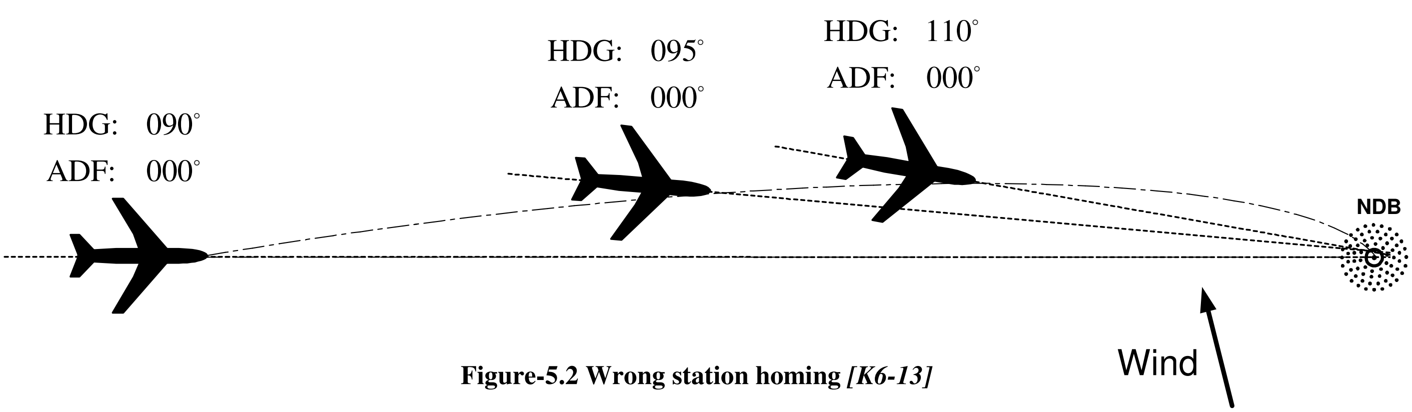


Figure-5.2 Wrong station homing *[K6-13]*

[18] If we are using a fix compass card, then the ADF needle will indicate a relative bearing w.r.t. the A/C nose HDG. However, if a rotating compass card is used, then correction can be made so that the ADF needle will point to the NDB magnetic bearing. Hereinafter we will assume that we are using a fix compass card.

- Correct Station Homing:
  - *Approximate wind Drift Angle (DA) to get back to TK: δ ≈ 5°*
  - *Approximate an extra angle to overcome future cross-wind once TK is regained: Extra ≈ 3°*
  - *A/C HDG is corrected to fly at: 90° + 5° + 3° = 98°*
  - *Notice that the ADF bearing and the A/C longitudinal differ by the Extra angle assigned to counter future wind.*
  - *Correction is achieved when both the ADF and the HDG needles are constant.*

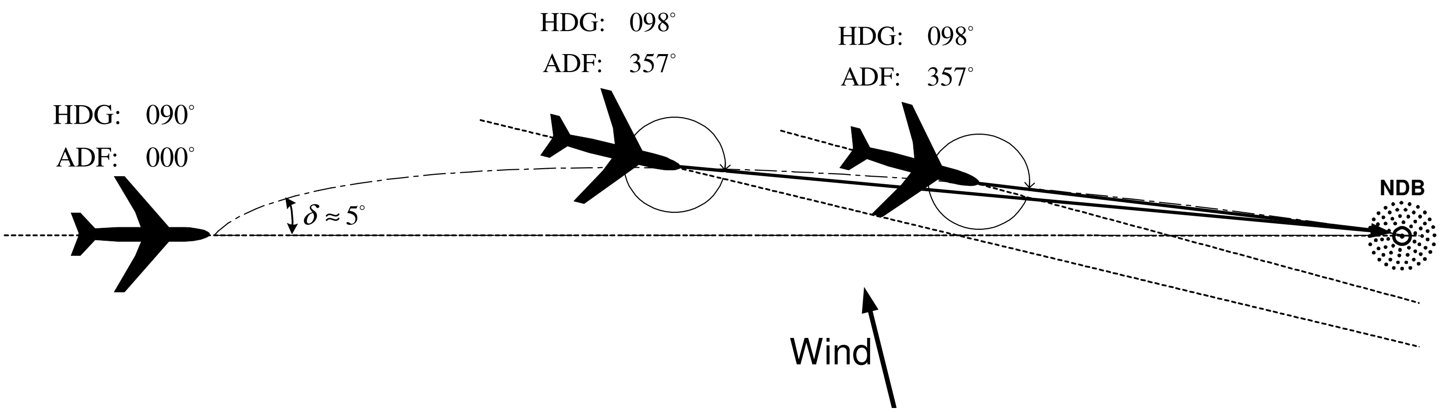


Figure-5.3 Correct station homing *[K6-13]*

3) *Triangulation Position Fix: To know where the A/C is located.*

- Tune ADF-Rx to an NDB
- Obtain the ADF bearing.
- Calculate the NDB magnetic bearing[19]
- Calculate the NDB true bearing[20]
- Place a corresponding line on the map
- Do the same by tuning to another NDB station
- Extend the lines on the map
- The intersection of the lines provides the 2D position fix[21] of the A/C.

- **<u>On the GND:</u>**

1) *Tx: NDB or NDB-DME systems.*
2) *Frequency: MF ≈ 220 – 550 kHz*
3) *The NDB sends a Morse ID code to the A/C ADF-Rx.*

[19] Using equation 5.1.
[20] That is, subtract 15^0 as explained in Figure-3.11.
[21] 2D position fix means to obtain the LAT and LON of the A/C at that time.

Figure-5.4 NDB GND station *[K4-3]*

- **<u>In the A/C:</u>**

1) *Rx: ADF-Rx system.*
2) *Frequency: MF ≈ 550 – 1750 kHz (commercial AM band)*
3) *ADF bearing needle points only to the tuned NDB.*
4) *When A/C flies toward an NDB the ADF bearing pointer indicates 000°.*
5) *When A/C flies above an NDB the ADF bearing pointer indicates 180°.*

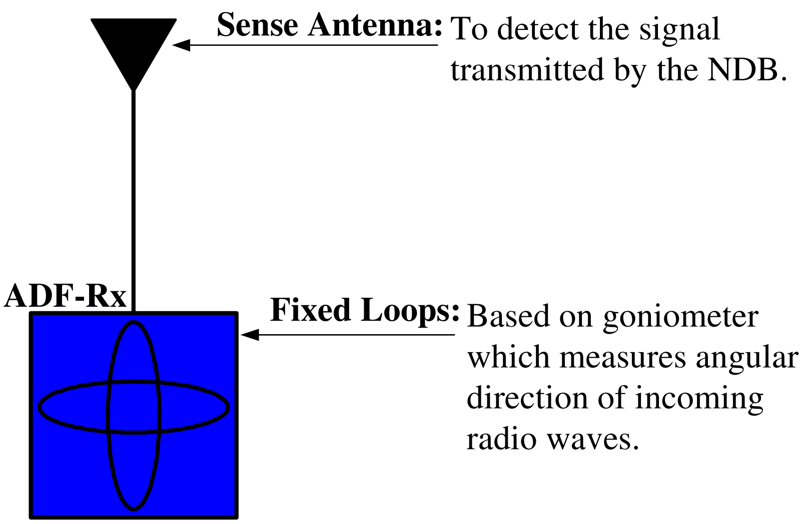


Figure-5.5 ADF–Rx system *[K3-13]*

- **Advantage:** ADF does not suffer from LOS[22] since it operates at the MF band.

- **Disadvantages:**

  1) *Errors:*
     - GND Wave: *error* $\approx \pm 5°$
     - Sky Wave[23]: *error* $\approx \pm 30°$

  2) *Quadrantal Error:*
     - Based on the bending of radio waves due to the A/C metal structure.
     - Swinging is required[24].
     - *Max error* $\approx \pm 10°$

  3) *Night Effect:*
     - At night ionosphere layer is low; therefore, strong sky waves, hence large error.
     - To minimize errors, at night, it is recommended to limit the use of GND stations.

  4) *Terrain Effect:*
     - Based on the reflection or bending of GND waves.
     - Mountain Effect: The radio wave signal is reflected from the side of mountains.
     - Coastal Effect: As the radio wave goes from land to water, the direction of the signal is changed.

  5) *Precipitation Static:*
     - Based on static formed when rain or snow or thunderstorm are in contact with antennas.

  6) *Icing Effect:*
     - Based on the accumulation of ice on antennas.

- **Future:** GPS should make ADF technology retire.

5.2 VHF Omni-directional Range – VOR

- **Principle:** Provides A/C radial w.r.t. a GND station. In other words, the VOR system only informs us of the A/C location as an entity seen by a GND VOR-Tx; however, we have no knowledge whatsoever on the HDG of the A/C. The radial of the A/C is obtained by taking the phase difference of 2 signals R & V transmitted by the GND station.

R : Reference Phase Signal
V : Variable Phase Signal
P : Phase Difference Between R & V

FROM : From the GND VOR-Tx
TO : Toward the GND VOR-Tx

[22] The higher the frequency of operation the more the technology will be limited by LOS.
[23] It is recommended to not operate ADF system near an NDB to make sure that sky waves will not be involved.
[24] Similar to a magnetic compass as described on Page-35.

$$\xi_{FROM} = \{\text{A/C Magnetic Radial w.r.t. VOR-Tx}\} = P \quad (5.2)$$

$$\xi_{TO} = \{\text{VOR-Tx Magnetic Radial w.r.t. A/C}\} = P \pm 180^{\circ} \quad (5.3)$$

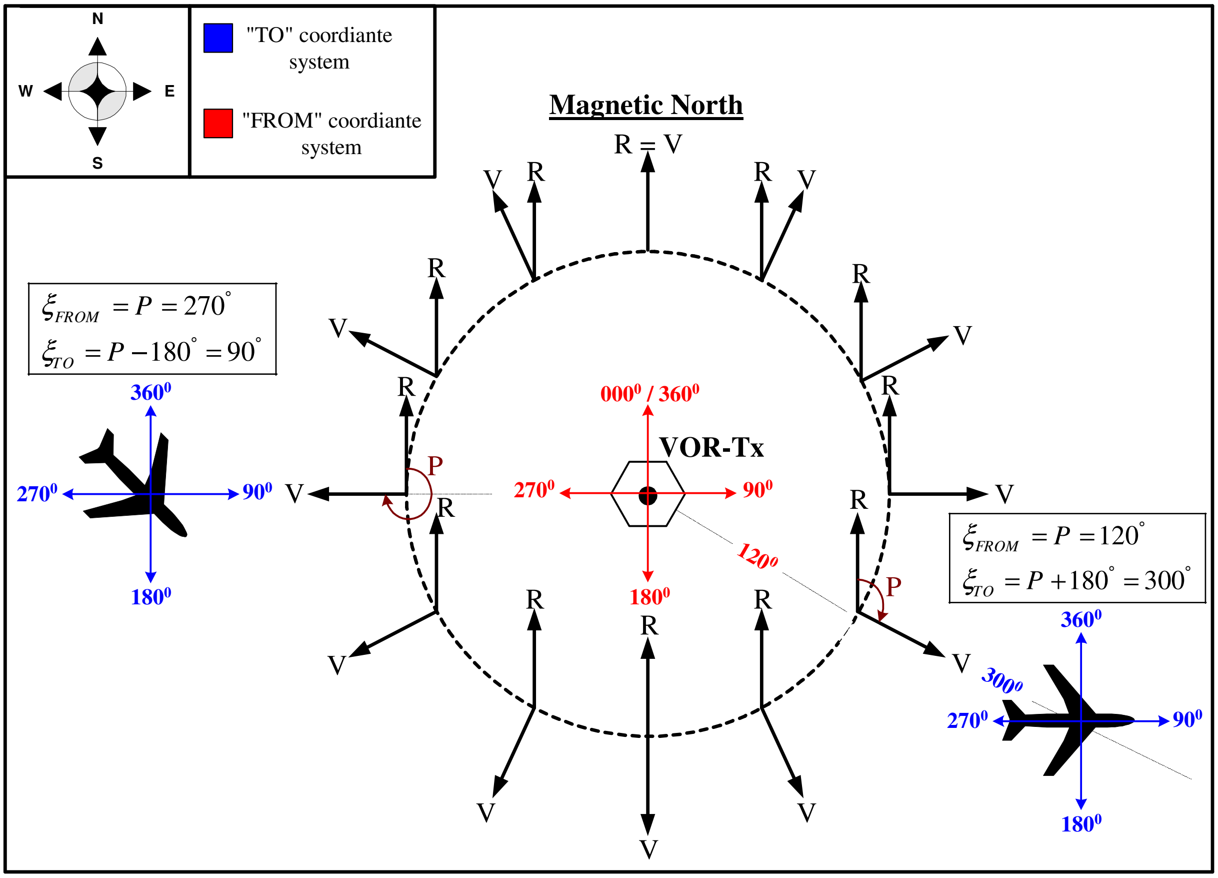


Figure-5.6 Examples illustrating the VOR principle *[K6-14]*

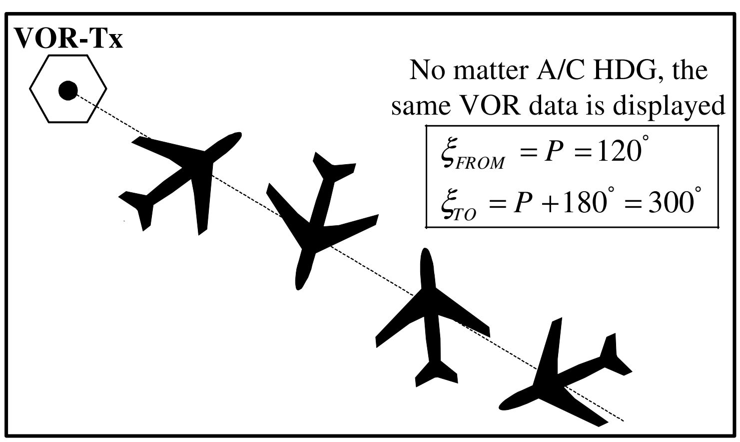


Figure-5.7 VOR does not provide A/C HDG; it only gives the radial occupied by the A/C

- **Applications:**

1) *V-Airway: Used to assign highways in the sky.*

2) *TK Intercept: To be able to get back to the TK due to crosswind. Simply fly toward the needle of the VOR display known as the Course Deviation Indicator (CDI) to ensure that the A/C is going in the direction of the VOR GND station.*

3) *Triangulation Position Fix: To know where the A/C is located, tune VOR-Rx to at least 2 VOR GND stations and obtain the 2D position fix.*

- **On the GND:**

1) *Tx: VOR-Tx or VOR-DME or VORTAC systems.*

2) *Frequency: VHF ≈ 108 – 118 MHz*
   - For Approach NAV: *108 – 112 MHz*
   - For Short-Range NAV: *112 – 118 MHz*
   - Number of Channels: *100*

3) *2 signals are emitted at the same time:*
   - Reference Phase Signal:
     - *Symbol: R*
     - *Modulation: FM*
     - *Rate: 30 Hz*
     - *Type: Non-directional*

   - Variable Phase Signal:
     - *Symbol: V*
     - *Modulation: AM*
     - *Rate: 30 revolutions per second (rps) ≡ 30 Hz*
     - *Type: Rotational*

4) *The VOR-Tx sends a Morse ID code to the A/C VOR-Rx.*

5) *VOR-Tx is also used for 2-way voice communication.*

Figure-5.8 VOR GND station *[K4-4]*

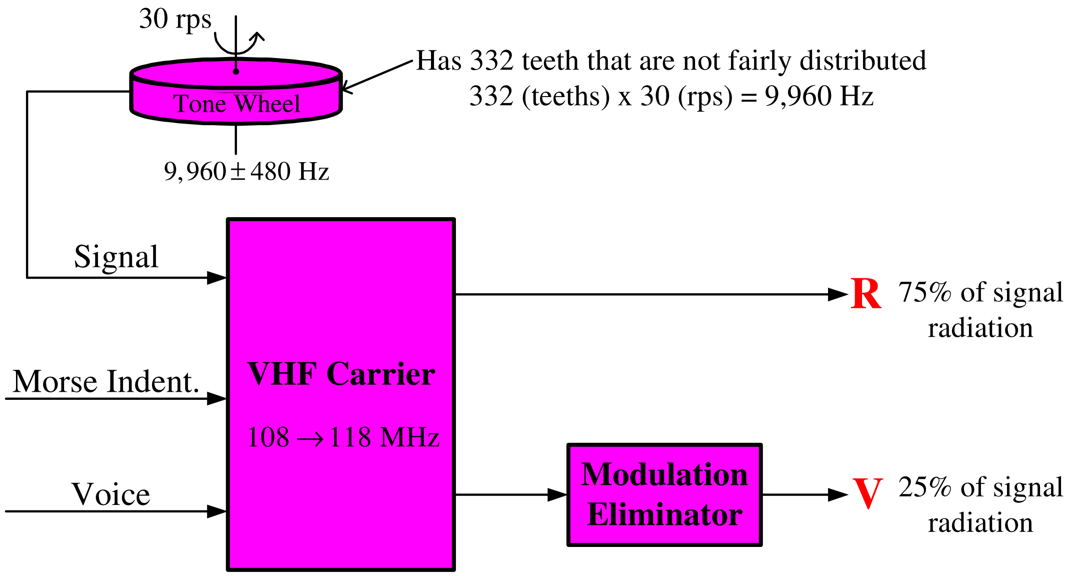


Figure-5.9 VOR–Tx system *[K3-14]*

- **<u>In the A/C:</u>**

  1) *Rx: VOR-Rx system.*
  2) *Frequency: VHF*
  3) *The phase difference P between R & V is calculated.*
  4) *A/C CDI shows the VOR radial reading. If CDI becomes defective a red flag will appear.*

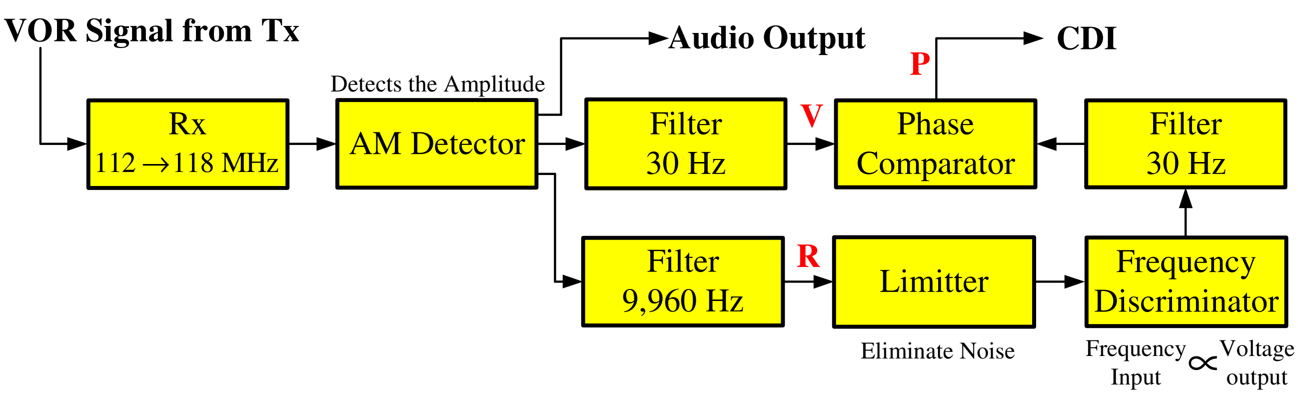


Figure-5.10 VOR–Rx system *[K3-15]*

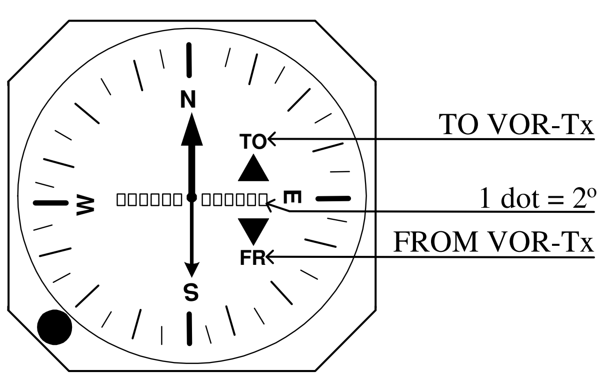


Figure-5.11 CDI *[K6-15]*

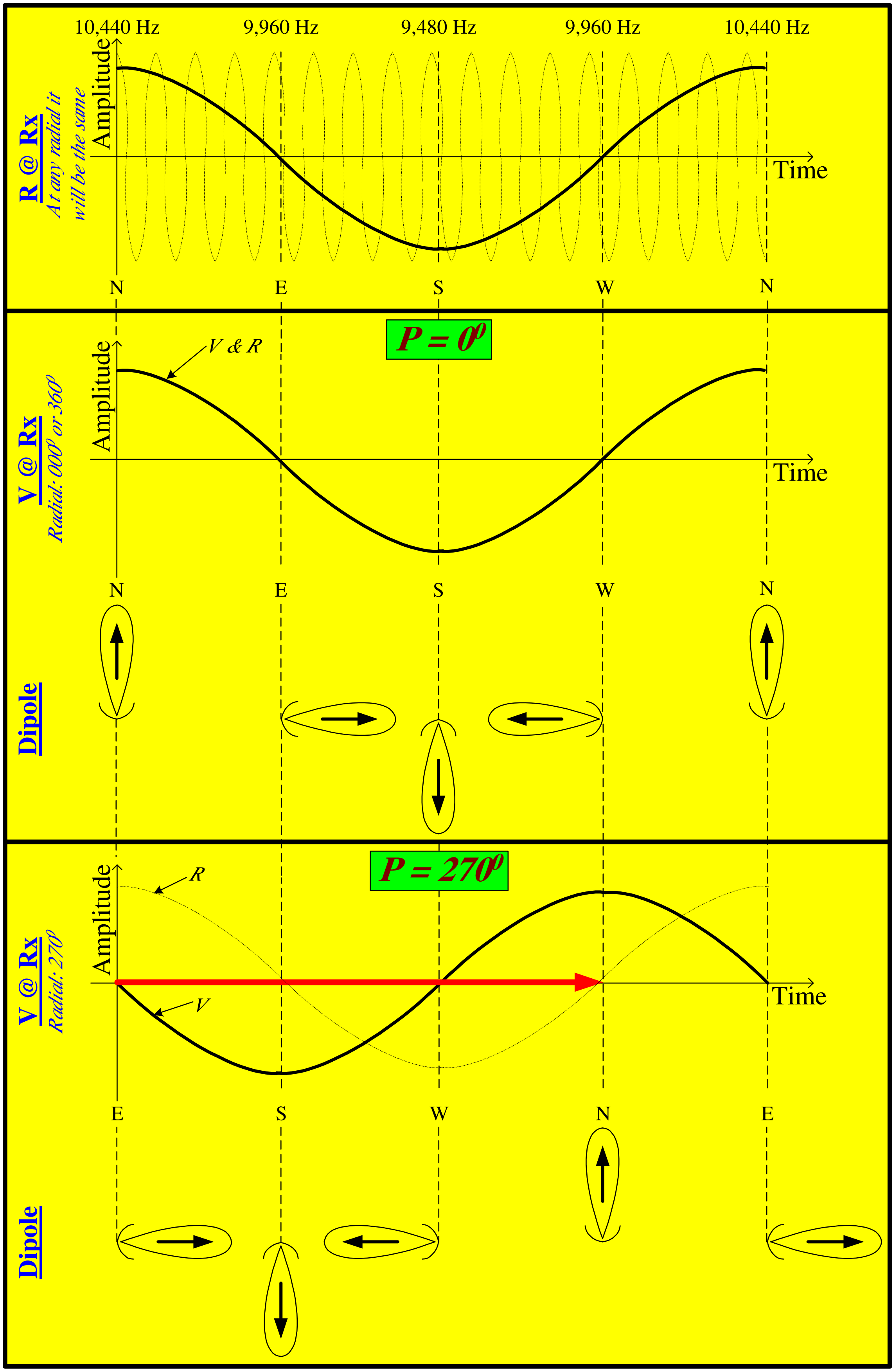


Figure-5.12 Examples of signals observed by the VOR-Rx at different radials ***[K3-16]***

- **Advantage:** VOR is more efficient than ADF since its indicator point to the GND VOR-Tx. Whereas ADF provides a relative bearing corresponding to the offset between the A/C longitudinal axis and the NDB, and hence does not point to the GND base beacon.

- **Disadvantages:**

  1) *Error ≈ ± 2°*

  2) *Limited to LOS due to VHF band operation*

  3) *VOR signals are either reflected or blocked or distorted due to:*
     - Buildings
     - Mountains
     - Fences
     - Power Lines
     - Etc.

  4) *At high ALT interference may occur between 2 GND stations operated at the same frequency.*

  5) *VOR does not provide the A/C HDG, it only points to the GND station.*

- **Future:** GPS is more accurate and efficient than VOR; however, VOR technology should still be used in A/C as a backup NAVAID in case a SAT communication problem occurs.

5.3 Distance Measuring Equipment – DME

- **Principle:** Provides distance between A/C and GND station. Ideally what we want from the DME system is the separation between the A/C and the DME station measured over GND (*D*); however, the DME usually outputs the slant distance (*S*) [25].

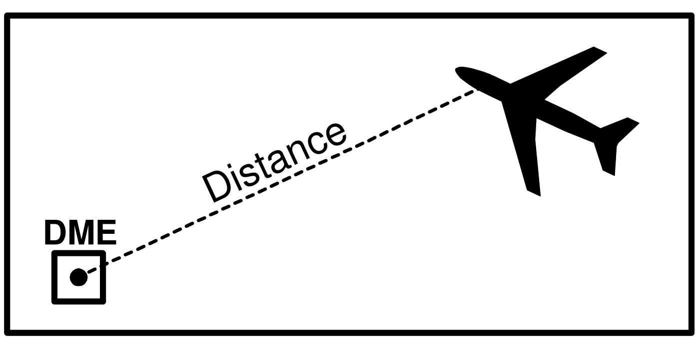


Figure-5.13 Example illustrating the DME principle

[25] For a graphical understanding of *D* and *S* refer to Figure-5.17.

- **<u>On the GND:</u>**

1) *Rx-Tx[26]: DME or NDB-DME or VOR-DME or TACAN or VORTAC systems.*

2) *Frequency: UHF ≈ 960 – 1215 MHz*
    - Number of Channels: *100*

3) *Each GND station is able to handle 100 A/Cs simultaneously.*

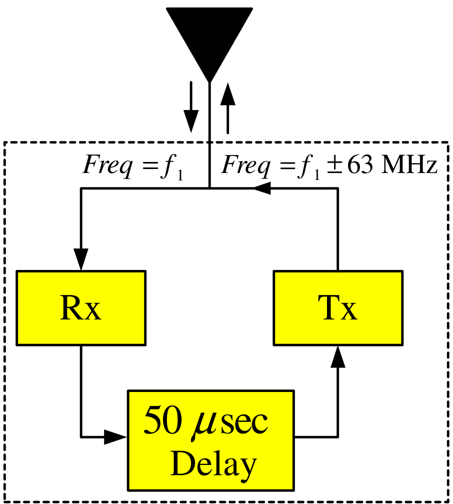


Figure-5.14 DME GND station *left:[K3-17] right:[K4-5]*

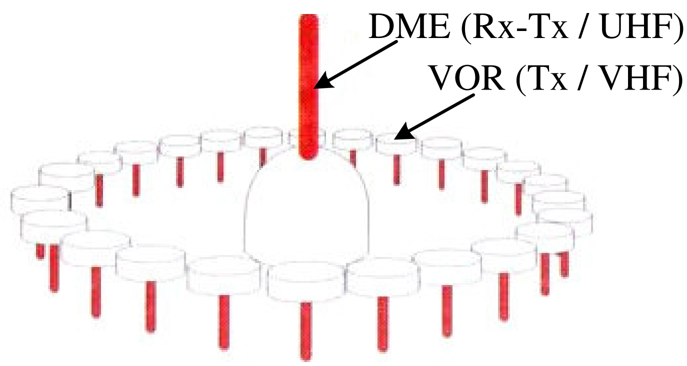


Figure-5.15 VOR-DME GND station *left:[K4-6] right:[K5-1]*

- **<u>In the A/C:</u>**

1) *Rx-Tx: DME system also known as (a.k.a) the Interrogator.*

2) *Frequency: UHF*

[26] Note that the DME system is different from ADF and VOR technologies, in the sense that the GND system is not only a Tx but also a Rx. Hence deducing from that, the airborne DME will also be a Rx-Tx system.

3) *Range of Operation: 150 – 200 miles ≈ 240 – 320 km*

4) *A/C DME displays:*
   - ❖ Distance in: *nm*
   - ❖ GS in: *kts*
   - ❖ Remaining time to get to GND station in: *minutes*

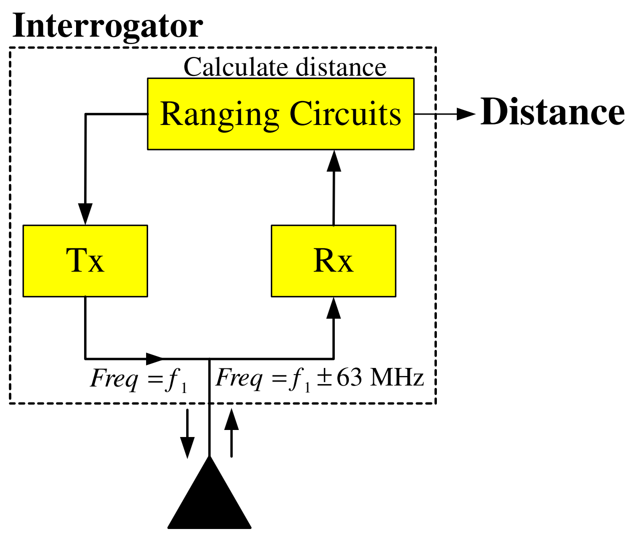


Figure-5.16 DME airborne system *[K3-17]*

- **Functionality:**

1) A/C DME Interrogator:
   - ❖ Interrogator transmit a signal[27] on one of the channels at: $Freq = f_1$

2) DME GND Station:
   - ❖ GND station receives the signal.
   - ❖ Add a delay of *50 μsec* to the signal
   - ❖ Signal is then transmitted to the A/C at: $Freq = f_1 \pm 63\ MHz$

3) A/C DME Interrogator:
   - ❖ Interrogator receives the signal
   - ❖ Measures the actual time that the signal traveled: $Time = \Delta T - 50\ \mu sec$
   - ❖ Calculates the distance using the following correspondence: $1\ nm \equiv 12\ \mu sec$

- **Advantage:** DME is rarely affected by precipitation static and thunderstorms.

- **Disadvantages:**

1) *Slant Error:* We use DME for the purpose of getting the distance *D*; however, the system will provide us the slant distance *S*. To overcome this inconvenience, we will show below that the larger *S* is w.r.t. the A/C ALT *A*, the smaller the *Error*.

[27] Each A/C transmits a signal with a specific pulse rate (Freq) and pattern.

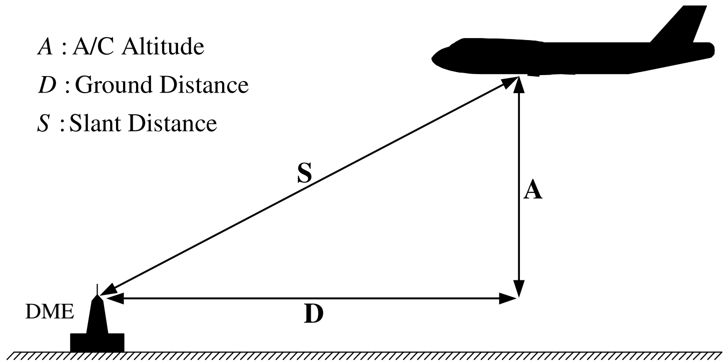


Figure-5.17 DME slant error

- **If $S >> A$, then $D \approx S$.**

1:	If: $S \gg A$ or $S^2 \gg A^2$	
2:	$S^2 = A^2 + D^2$ or $D = \sqrt{S^2 - A^2} \approx \sqrt{S^2} = S$	(5.4)
3:	Then: $D \approx S$	

- **If $S = 5A$, then $Error \approx 2\%$.** Also, **If $S > 5A$, then $Error < 2\%$.**

1:	If: $S = 5A$	
2:	$D = \sqrt{S^2 - A^2} = \sqrt{25A^2 - A^2} = \sqrt{24A^2} \approx 4.9A$	
3:	$Error = \frac{\lvert estimate - real \rvert}{real} \times 100 = \frac{\lvert S - D \rvert}{D} \times 100 \approx \frac{\lvert 5A - 4.9A \rvert}{4.9A} \times 100 = 2.041\% \approx 2\%$	(5.5)
4:	Then: $Error \approx 2\%$	

- **If $S = A$, then $Error = 100\%$**[28].

1:	If: $S = A$	
2:	$D = \sqrt{S^2 - A^2} = \sqrt{A^2 - A^2} = 0$	
3:	$Error = \frac{\lvert estimate - real \rvert}{real} \times 100 = \frac{\lvert S - D \rvert}{D} \times 100 \approx \frac{\lvert A - 0 \rvert}{0} \times 100 = \infty = 100\%$	(5.6)
4:	Then: $Error \approx 100\%$	

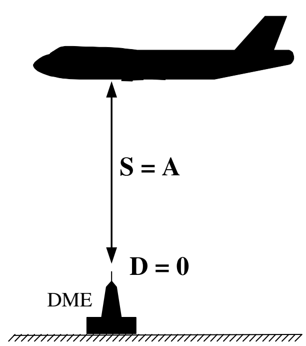


Figure-5.18 Greatest DME slant error

[28] When the A/C is above the DME GND station we expect to have a null reading; however, the A/C DME display will output the ALT.

2) *Limited to LOS due to UHF band operation*

- **Future:** GPS is more accurate and efficient than DME; however, DME technology should still be used in A/C as a backup NAVAID in case a SAT communication problem occurs.

5.4 Tactical Air Navigation – TACAN

- **Principle:** Provides A/C bearing and distance w.r.t. a GND station for MIL purposes. The bearing part of this system is similar to VOR, but quite unique for the nature of MIL operation. As for the distance measurement capability, it is in fact obtained through the integrated DME system within the TACAN GND station.

- **On the GND:**

1) *Rx-Tx: TACAN or VORTAC systems.*

2) *Frequency: UHF ≈ 960 – 1215 MHz*
    - ❖ Number of Channels: *252*

Figure-5.19 TACAN GND station *[K4-7]*

- **In the A/C:**

1) *Rx-Tx: TACAN system.*
2) *Frequency: UHF*
3) *Range of Operation: 200 miles ≈ 320 km*

- **Advantages:**

  1) *Rejects bounced signals*

  2) *Low power consumption*

  3) *Resistant to:*
     - Shock
     - Vibration
     - Electro-magnetic Interference (EMI)

  4) *Flawless in the world's most environmentally severe sites:*
     - Snow
     - Humidity
     - Rain
     - Fungus
     - Sand
     - Dust

  5) *Maintenance free antennas, since it has no moving parts.*

  6) *Combines bearing and distance capabilities together.*

  7) *If the bearing Tx becomes defective, the facility will remain active as a DME GND station.*

- **Disadvantages:**

  1) *Bearing Error* $< \pm 3.5°$
  2) *Distance Slant Error*
  3) *Limited to LOS due to UHF band operation.*

- **Future:** GPS is more accurate than TACAN; however, TACAN technology is a stable MIL NAVAID and should remain in operation for the years to come.

5.5 VOR and TACAN – VORTAC

- **Principle:** GND system with both VOR and TACAN for bearing and distance purposes. In a broader sense, instead of having VOR, and TACAN GND stations separately, we could simply join them into a single GND station known as VORTAC.

- **On the GND:**

  1) *Rx-Tx: VORTAC system.*

  2) *Frequency:*
     - *VHF ≈ 108 – 118 MHz (VOR)*
     - *UHF ≈ 960 – 1215 MHz (TACAN which has an integrated or built-in DME)*

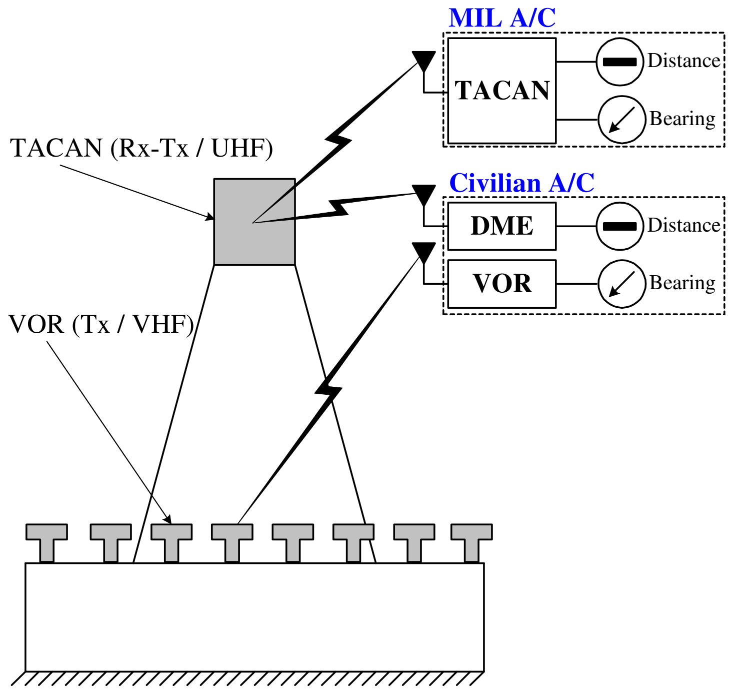


Figure-5.20 VORTAC GND station *left:[K4-8] right:[K3-18]*

- **<u>In the A/C[29]:</u>**

  1) *CIV A/C:*
     - ❖ Rx: VOR-Rx system.
     - ❖ Rx-Tx: DME Interrogator.

  2) *MIL A/C:*
     - ❖ Rx-Tx: *TACAN system*.

- **<u>Advantage:</u>**

  1) *Combining GND stations for CIV and MIL is quite feasible in terms of:*
     - ❖ Cost
     - ❖ Operations
     - ❖ Maintenance

  2) *Other advantages enumerated for VOR[30] and TACAN[31] are also present here.*

- **<u>Disadvantages:</u>** The same disadvantages enumerated for VOR[30] and TACAN[31] are also present here.

- **<u>Future:</u>** GPS is more accurate than VORTAC; however, VORTAC technology is an optimized approach for a NAVAID GND station, and hence should remain in operation.

---

[29] VORTAC is a GND station. But to take advantage of this station different equipments are needed within the A/C depending if the vehicle is used for CIV or MIL purposes.
[30] For VOR advantage and disadvantages refer to Page-59.
[31] For TACAN advantages and disadvantages refer to Page-64.

5.6 Random or Area Navigation – RNAV

- **Principle:** Provides A/C bearing and distance w.r.t. a 3D artificial reference point known as Waypoint[32] (WPT). In fact, the main motivation to navigate using computerized WPTs is to obtain optimized air routes from departure to arrival.

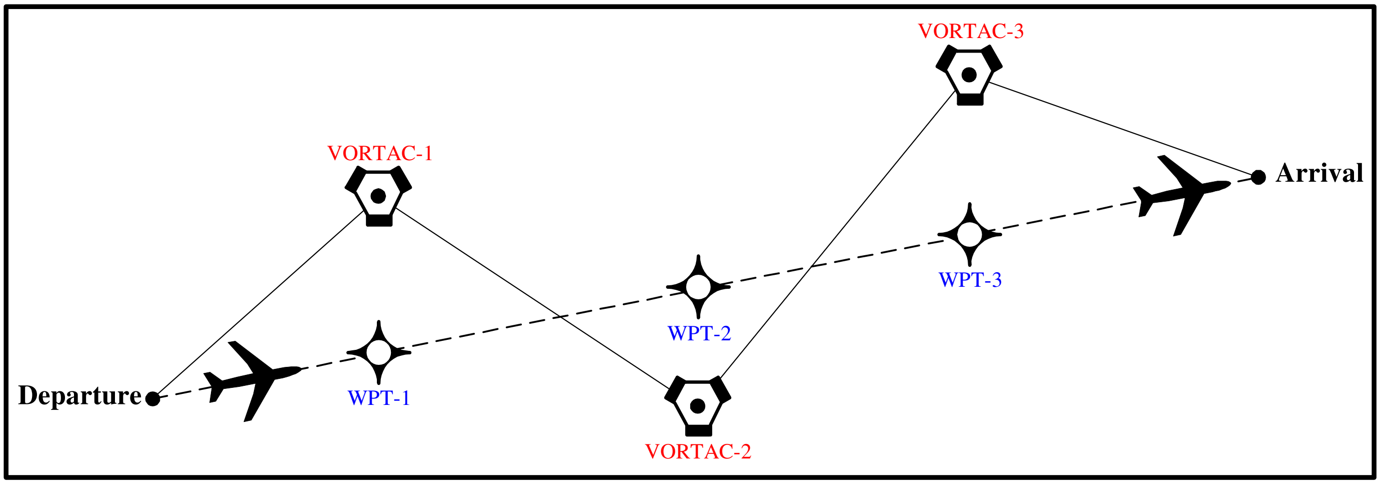


Figure-5.21 Example illustrating the RNAV principle using VORTAC GND stations *[K6-16]*

- **Position Fix:** To obtain WPTs, we need to have the present A/C 3D[33] position fix. There are 3 general ways to do that using either:

  1) *GND Stations and A/C Radar:*

     ❖ *GND Stations:* VOR-DME or VORTAC to obtain bearing and distance; which could eventually be transformed to A/C LAT and LON.

     ❖ *A/C Radar:* Radio Altimeter (RA) to obtain the A/C ALT.

  2) *A/C Self-Contained Systems:* INS or DNS[34]

  3) *Orbital SAT System:* GPS[34]

- **In the A/C:** Airborne *RNAV System* performs 2 important tasks:

  1) *Identifies WPT needed:* RNAV calculates WPTs or uses already loaded WPTs from a NAV Database (DB) based on the present A/C position and the flight plan required to reach destination.

  2) *Outputs relative A/C position:* Once the WPT is identified in 3D, then the A/C bearing and distance is obtained w.r.t. it. Now, the A/C simply needs to fly toward that WPT.

[32] WPT could also be thought as a 3D point where we want the A/C to be after some time has elapsed.
[33] 3D represents the LAT, LON, and ALT of the A/C.
[34] INS, DNS, and GPS are systems that provide continuous A/C 3D position fixes; they will be explained later in this chapter.

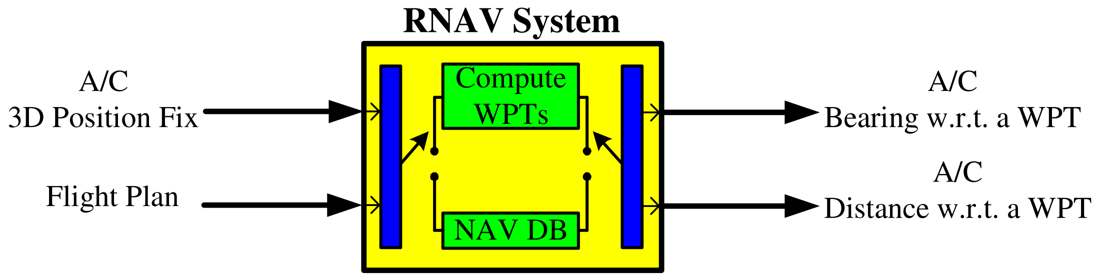


Figure-5.22 RNAV airborne system

3) *Secondary Outputs:* Some RNAV systems also outputs:

- ❖ Estimated Time of Arrival (ETA) to next WPT
- ❖ Necessary IAS required to achieve ETA
- ❖ Estimated fuel remaining at destination

- **Advantages:**

1) *More direct, efficient, and flexible routes are generated.*

2) *Arrive faster at destination (i.e. time effective).*

3) *Requires less fuel to reach destination (i.e. cost effective).*

4) *More disperse NAV (i.e. full use of airspace).*

5) *More traffic is possible at random locations; hence, less traffic is obtained in a specific geographical area.*

- **Disadvantages:** Major errors are those involved in obtaining the A/C position fix using GND stations.

1) *Same errors*[35] *as those of VOR, DME, or VORTAC.*

2) *A possible way to obtain fictitious WPTs is through corresponding GND stations; however, they are limited by operation range.*

3) *The airway obtained using RNAV is tighter than the V or J-airway:*

$$\text{RNAV-airway width} = 8\ nm \approx 15\ km \tag{5.7}$$
$$\text{V or J-airway width} = 10\ sm \approx 16\ km \tag{5.8}$$

- **Future:** It is quite evident that INS or DNS or GPS facilitates the use of RNAV in oceanic airspace since no stations are needed. Also, GPS is a more accurate way to obtain A/C position fix as opposed to other methods; and therefore, the use of GPS should make the GND station technology retire in the years to come.

[35] Most important errors are those of signal reflection of VOR radials and slant error involved in the DME process.

5.7 Combined Displays

Several instruments are combined together to facilitate pilot-A/C interface, and hence lower the crew workload.

5.7.1 Radio Magnetic Indicator – RMI

- **Indicator Characteristics:**

1) *Flux-valve compass card that indicates the A/C magnetic HDG.*
2) *A needle driven by ADF-Rx indicating the NDB[36] magnetic bearing w.r.t. A/C.*
3) *A needle driven by VOR-Rx indicating the VOR GND station bearing (TO) w.r.t. A/C.*
4) *If we extend the bearing lines of the 2 GND stations we obtain the position fix of the A/C.*

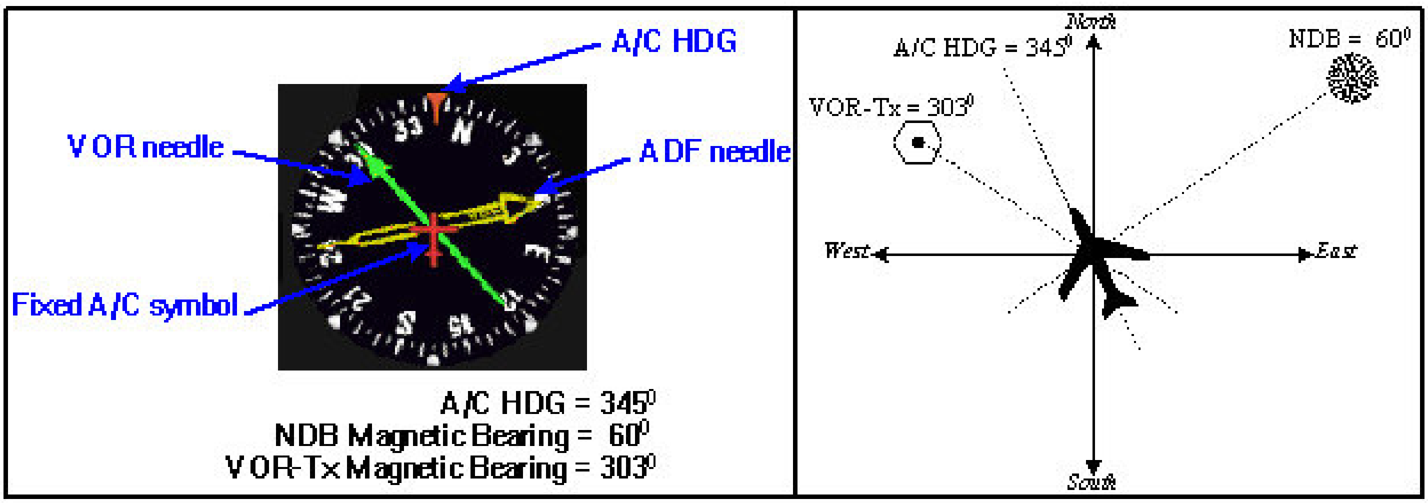


Figure-5.23 RMI ***left:[K5-2]***

5.7.2 Horizontal Situation Indicator – HSI

- **Indicator Characteristics:**

1) *DG[37] to indicate A/C HDG.*
2) *Warning flags to indicate loss or unreliable information.*
3) *Manually adjust to desired A/C HDG.*
4) *Manually adjust to a tuned GND station.*
5) *Vertical and horizontal guidance during the Approach/Landing phase.*

[36] Using ADF functionality from the RMI simplifies NAV, since we will obtain the NDB magnetic bearing and not the ADF relative bearing as explained on Page-51.
[37] To read more on DG refer to Page-33.

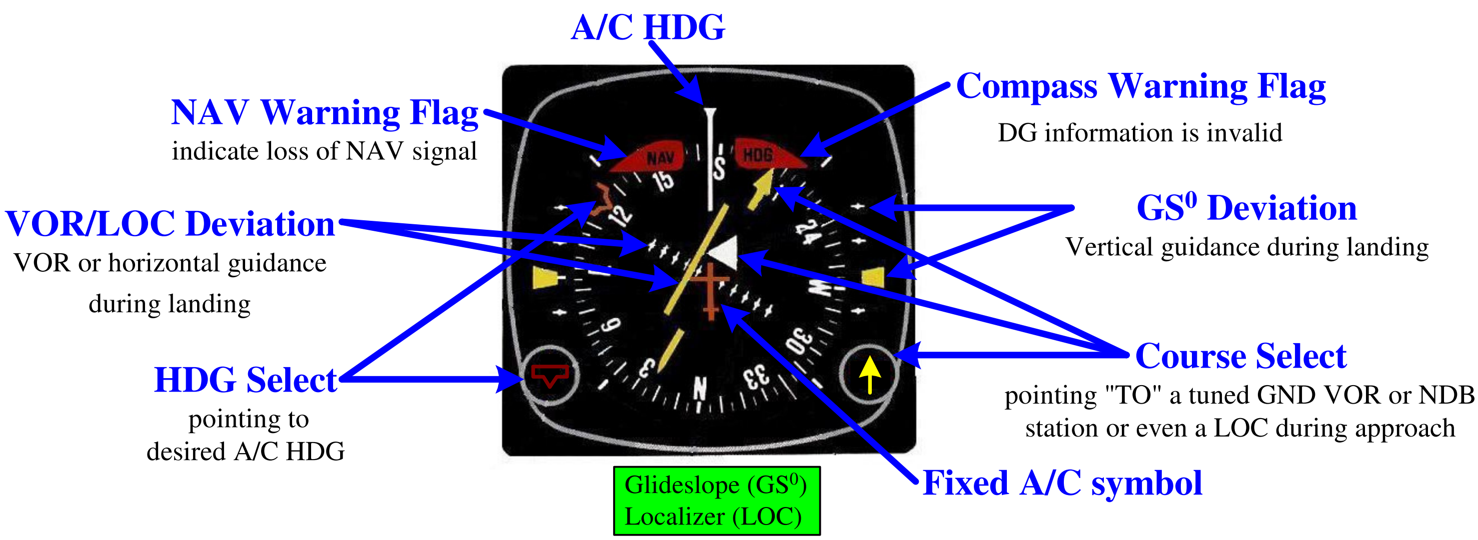


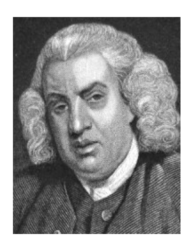
Figure-5.24 HSI ***[K5-3]***

Chapter 6

Long-Range NAVAIDS

Knowledge is of two kinds. We know a Subject ourselves, or we know where we can find information upon it.

— Samuel Johnson



6.1 Long Range Navigation (revision-C) – LORAN-C

- **Principle:** Provides A/C position fix (2D)[38]. In fact, this technology is known as a hyperbolic system since it determines NAV fix using hyperboles or parabolic lines (***black***) generated from the intersection of signals (***blue*** & ***red***) radiated by GND stations. Also, notice the formation of some straight lines (***green***).

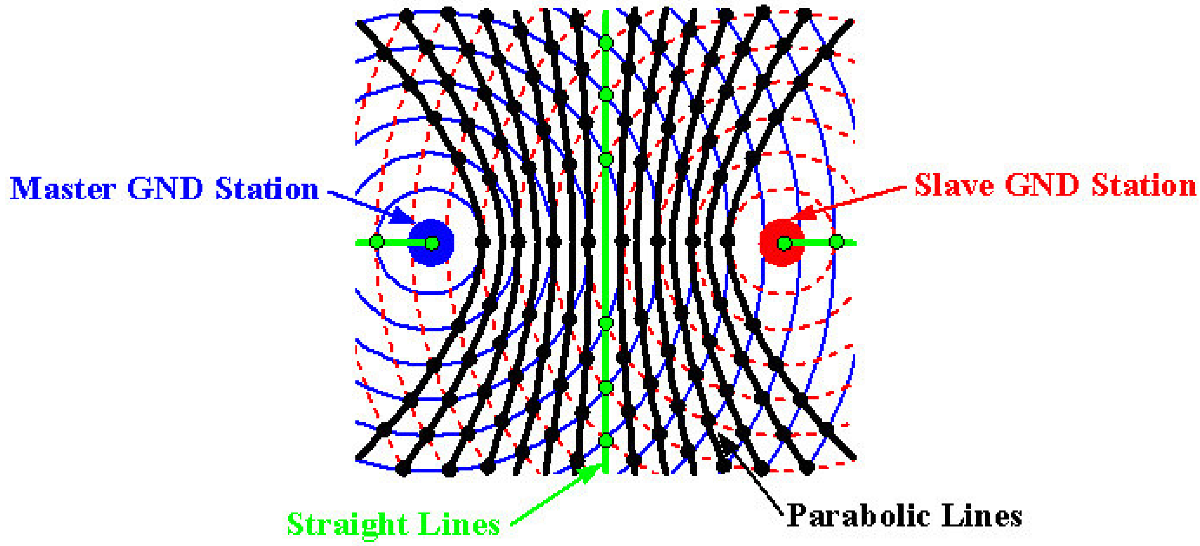


Figure-6.1 Formation of the hyperbolic grid *[K6-17]*

- **Position Fix:** To obtain the A/C position fix at least 2 hyperbolic grids are required. This means that at least 2 Line Of Position (LOP) have to be generated from a single *master* station, and at least 2-*slave* GND stations.

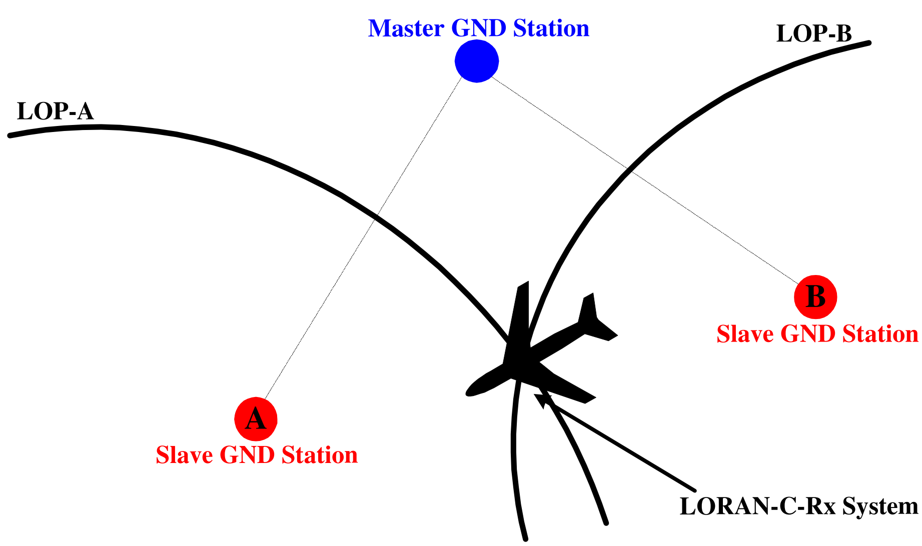


Figure-6.2 Position fix using LORAN-C system *[K6-18]*

[38] 2D represents the LAT, and LON of the A/C.

- **<u>On the GND:</u>**

  1) *Tx: Master & Salve LORAN-C-Tx systems.*

  2) *Frequency: LF ≈ 90 – 110 kHz*

  3) *LORAN-C signal pulses propagate using GND waves.*

  4) *Possible Tx topologies:*
     - Trial: *1-master and 2-slave stations.*
     - Star: *1-master and 3-salve stations.*
     - Square: *1-master and 4-salve stations.*

  5) *The master station transmits a sequence of 9-pulses.*

  6) *After a delay*[39]*, the slave station will also emit a sequence of 8-pulses.*

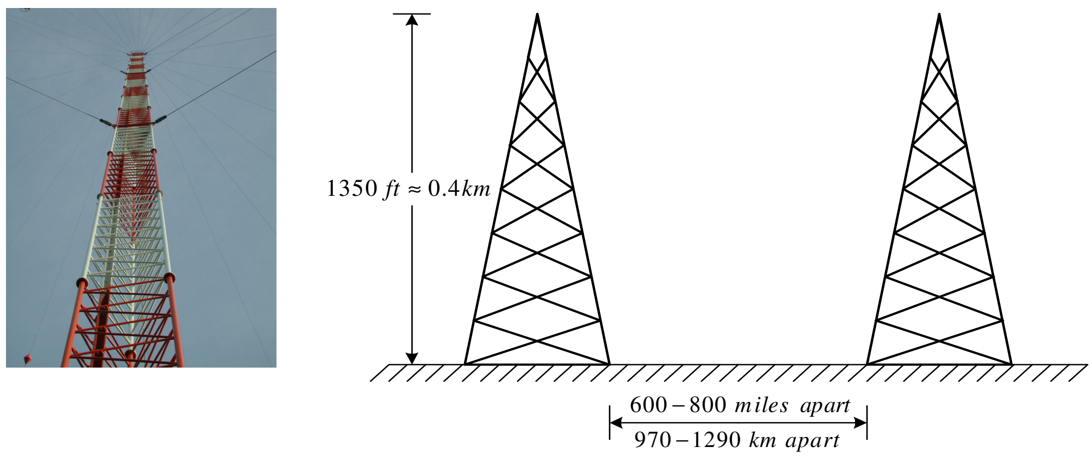


Figure-6.3 LORAN-C GND stations *left:[K4-9]*

- **<u>In the A/C:</u>**

  1) *Rx: LORAN-C-Rx system.*

  2) *Frequency: LF*

  3) *Highly selective Rx in order to avoid interference from other signals.*

  4) *When the 9-pulses from the master station reaches the A/C, the Rx will start counting the time (Δt) it takes for the slave 8-pulse signals to reach the airborne Rx.*

  5) *To calculate the A/C position fix, we need to know the position of the master and slave stations, the station separation distance, and Δt.*

[39] Note that the delay introduced here is dependent on the separation distance between the specific master-slave pair stations.

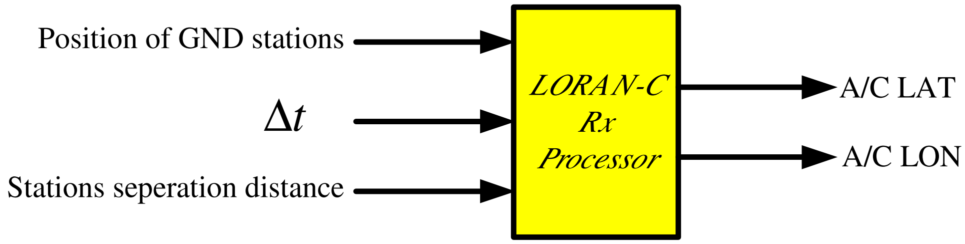


Figure-6.4 LORAN-C airborne processor

6) *There exist Rx with dual LORAN-C and GPS usage. The processor within this Rx will calculate and output:*
   - A/C Position: LAT & LON
   - GS
   - Wind Drift
   - WPT information
   - ETAs
   - Airport data
   - Etc.

- **Advantages:**

  1) *LORAN-C does not suffer from LOS since it operates at LF band.*

  2) *Hyperbolic grid NAV provides a more direct route similar to WPT NAV.*

  3) *Signal propagation is based on GND waves; therefore large travel ranges[40] are possible.*

- **Disadvantages:**

  1) *Error ≈ ± 150 m*

  2) *Ground Wave Propagation Error: The velocity at which the signal travels may vary, and hence some offset may be introduced in calculating the A/C position fix.*

  3) *There are not enough LORAN-C GND stations in the world to cover all possible air routes.*

- **Future:** GPS should make LORAN-C technology retire.

6.2 Optimized Method for Estimated Guidance Accuracy – OMEGA

- **Principle:** Provides A/C position fix (2D). This technology is based on NAV using a hyperbolic grid, which is quite similar to the LORAN-C.

[40] NAV ranges in the *1000's of miles ≈ 1600 km*

- **Position Fix:** To obtain the A/C position fix at least 2 LOPs are required as shown in Figure-6.2 above. The only difference is that in the OMEGA process we need 3 GND stations without tagging them as master or salve like we did using LORAN-C.

- **On the GND:**

1) *Tx: Only 8 OMEGA-Tx systems exist in the world.*

2) *Frequency: VLF ≈ 10.2 – 13.6 kHz*

3) *OMEGA signals propagate using sky waves.*

4) *Each GND station could transmit 4 possible time-shared signals*[41] *(10.2, 13.6, 11.33, or 11.05 kHz).*

5) *In addition to the signals above a unique ID signal is emitted from each station.*
   - ❖ Norway / Aldra: 12.1 kHz
   - ❖ Liberia / Monrovia: 12.0 kHz
   - ❖ US / Hawaii / Haiku: 11.8 kHz
   - ❖ US / North Dakota / La Moure: 13.1 kHz
   - ❖ France / Réunion: 12.3 kHz
   - ❖ Argentina / Golfo Nuevo: 12.9 kHz
   - ❖ Australia: 13.0 kHz
   - ❖ Japan / Tsushima: 12.8 kHz

6) *Transition-time from one signal Freq to another ≈ 0.2 seconds.*

7) *The signal transmission scheme repeats every 10 seconds.*

8) *GND based atomic clocks are used to synchronize stations among each other.*

10 Seconds

LOCATION	0.9	0.2	1.0	0.2	1.1	0.2	1.2	0.2	1.1	0.2	0.9	0.2	1.2	0.2	1.0	0.2
Norway	10.2		13.6		11.33		12.1		12.1		11.05		12.1		12.1	
Liberia	12.0		10.2		13.6		11.33		12.0		12.0		11.05		12.0	
US / Hawaii	11.8		11.8		10.2		13.6		11.33		11.8		11.8		11.05	
US / North Dakota	11.05		13.1		13.1		10.2		13.6		11.33		13.1		13.1	
France / Réunion	12.3		11.05		12.3		12.3		10.2		13.6		11.33		12.3	
Argentina	12.9		12.9		11.05		12.9		12.9		10.2		13.6		11.33	
Australia	11.33		13.0		13.0		11.05		13.0		13.0		10.2		13.6	
Japan	13.6		11.33		12.8		12.8		11.05		12.8		12.8		10.2	

Figure-6.5 Time-frequency transmission scheme for OMEGA GND stations ***[K6-19]***

[41] The 8 worldwide GND Tx stations are time-frequency multiplexed. In other words, if one of the 8 possible GND stations transmits a signal with a specific frequency at a given time, then none of the other remaining 7 stations can transmit a signal with that frequency at that moment as in Figure-6.5.

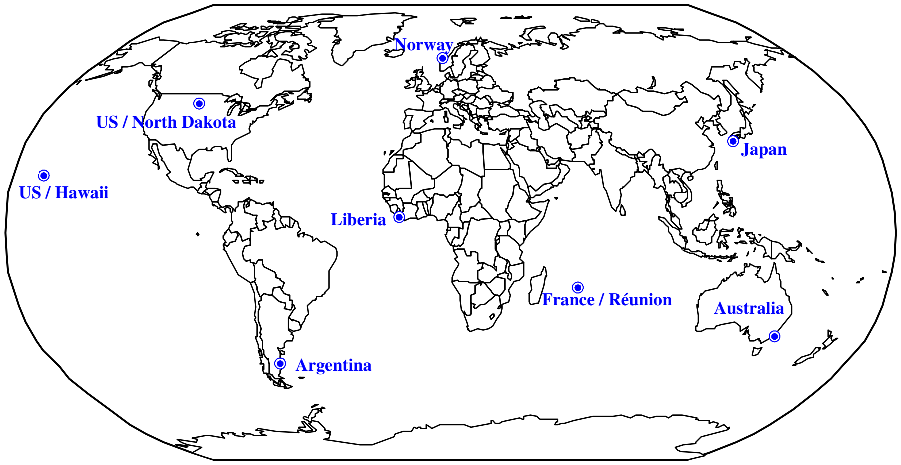


Figure-6.6 Location of the OMEGA GND Tx stations *[K6-19]*

- **In the A/C:**

1) *Rx: OMEGA-Rx system.*
2) *Frequency: VLF*
3) *Range[42] of Operation: 6,000 miles ≈ 10,000 km [43]*
4) *Highly selective Rx in order to avoid interference from other signals.*

- **Advantages:**

1) *OMEGA does not suffer from LOS since it operates at VLF band.*
2) *Hyperbolic grid NAV provides a more direct route similar to WPT NAV.*
3) *Sky wave propagation uses the reflective property of the ionosphere layer; hence large travel ranges are possible.*

- **Disadvantages:**

1) *Error ≈ ± 0.5 miles ≈ ± 1 km*

2) *Sky Wave Propagation Error: The velocity at which the signal travels may vary, and hence some offset may be introduced.*

3) *Diurnal Error: The ionosphere layer varies in height[44] during day and night and therefore errors are generated. That is, for position fix 3-stations are needed, and in most cases these GND stations are not aligned within the same time zone; therefore different ionosphere heights will result at different geographical locations.*

4) *Maintenance of the OMEGA GND stations is quite costly.*

[42] The large range of operation explains why only 8-GND stations are required to have a worldwide coverage.
[43] To get a sense of what *10,000 km* is, think of it as going from Montréal to Vancouver and back to Montréal.
[44] For more on the effect of daytime / nighttime on the ionosphere layer refer to Page-44.

- **Future:** GPS made the OMEGA retire on *September-30-1997*. However, The North Dakota station is still used by the US Navy for VLF submarine communications.

6.3 Inertial Navigation System or Inertial Reference System – INS or IRS

- **Principle:** Provides A/C velocity (3D) and position fix (3D). In fact, INS is based on DR[45], i.e. we first need to obtain the A/C vectorial acceleration ($\vec{a}$), then integrate ($\int$) once to obtain the velocity, and finally integrate a second time to get the position. Also, what makes this technology quite amazing is that it is a self-contained system; hence, no GND stations are required for operation.

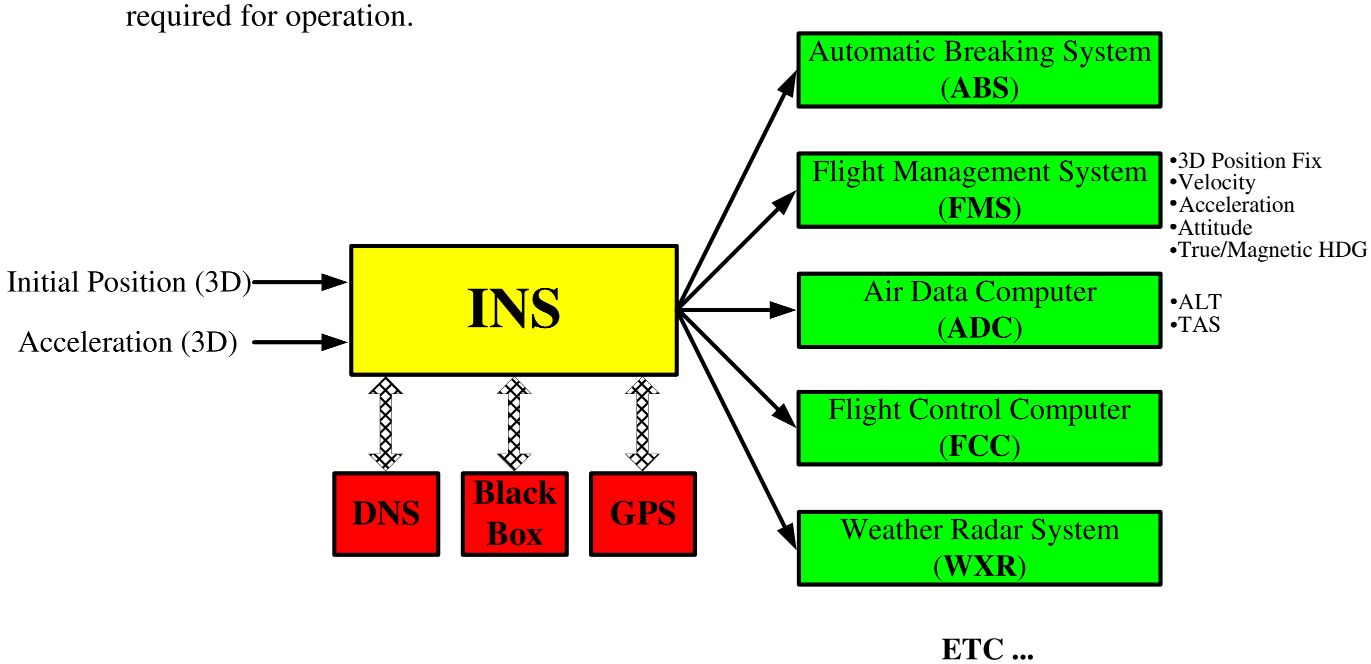


Figure-6.7 Airborne INS interfaces

- **In the A/C:** There are 2-types of INS:

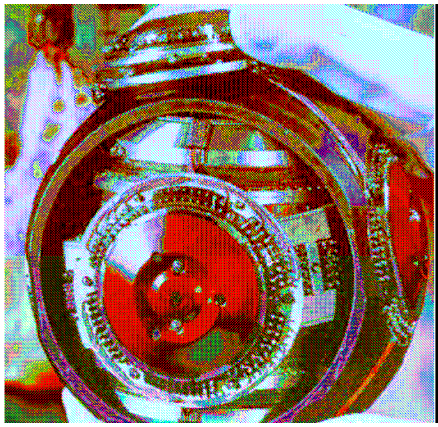
1) *Stable-Platform INS or Gimballed INS:*

❖ The stable-platform isolates the gyroscopes and accelerometers from the A/C angular motion, and hence remains in-synch with the earth coordinate system.

❖ Contains 3 Gyroscopes (G):
  - G_{ROLL}
  - G_{PITCH}
  - G_{YAW}

❖ Contains 3 movable Accelerometers (A):
  - $A_{LAT} = A_{N\text{-}S}$
  - $A_{LON} = A_{W\text{-}E}$
  - A_{ALT}

[45] For more on DR refer to Page-3.



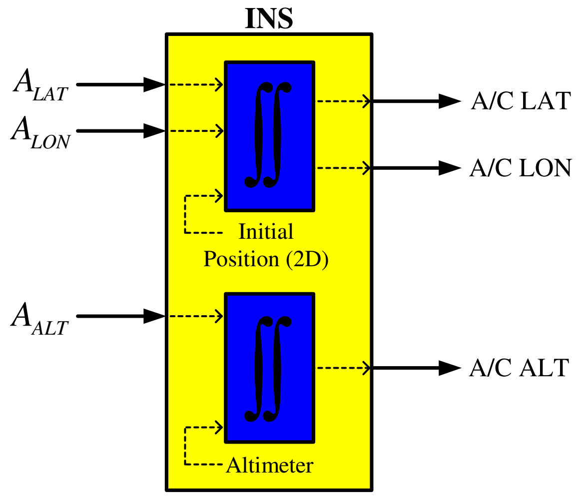


Figure-6.8 Stable-platform INS *left:[K4-10]*

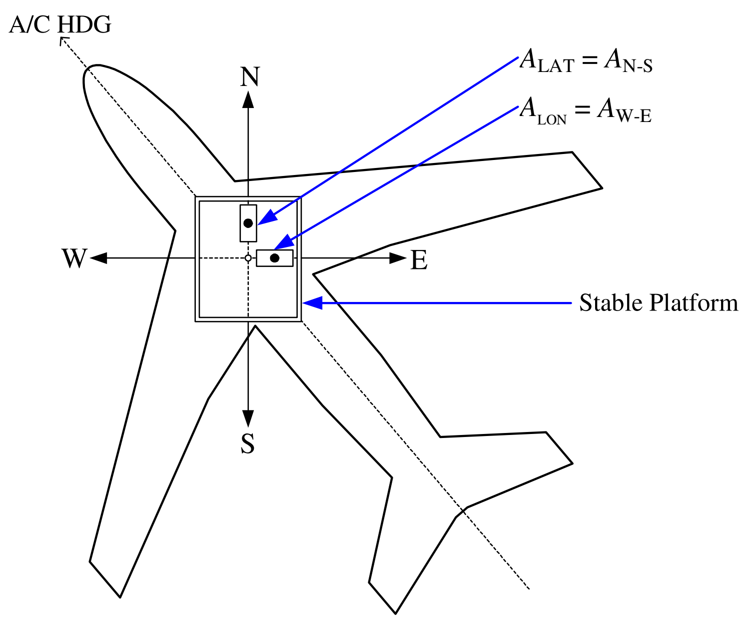


Figure-6.9 2D-view of a stable-platform INS *[K3-19]*

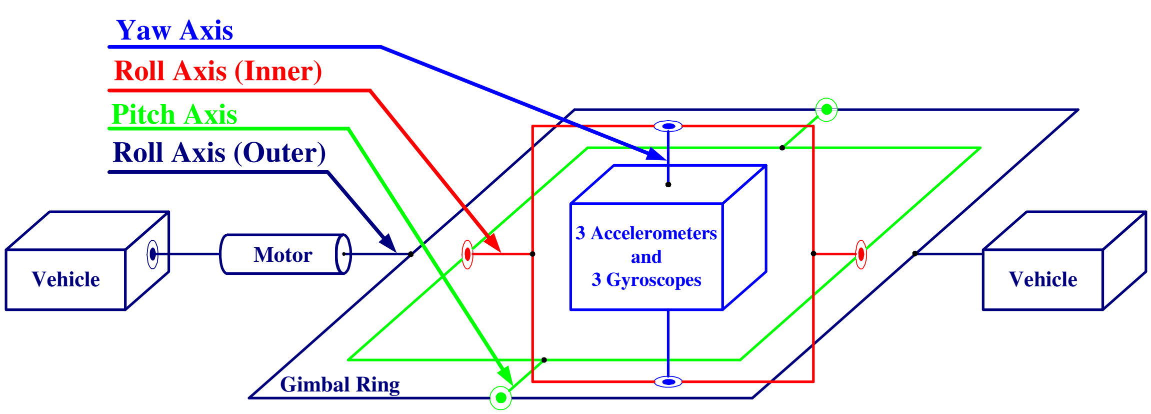


Figure-6.10 3D-view of a stable-platform INS *[K3-20]*

2) *Strap-Down INS:*

- This type of INS has no moving parts; and therefore, the accelerometers are solidly connected[46] to the airframe and gyroscopes are well aligned with the A/C *X-Y-Z* coordinate[47] system.

- Contains 3 laser gyroscopes:
  - $G_{ROLL} = G_X$
  - $G_{PITCH} = G_Y$
  - $G_{YAW} = G_Z$

- Laser gyroscope:
  - *2-laser light beams are sent one clockwise, and the other counter-clockwise.*
  - *Doppler Effect: Beam going against the rotation produces high Freq.*
  - *Therefore we want to determine: Δf = Freq difference of the two light beams.*
  - *If $\Delta f = 0$: then the fringing pattern is stationary and there is no angular rotation in the Z-axis.*
  - *If $\Delta f \neq 0$: then the fringing pattern moves at a rate $\propto \Delta f \propto$ angular input rate.*

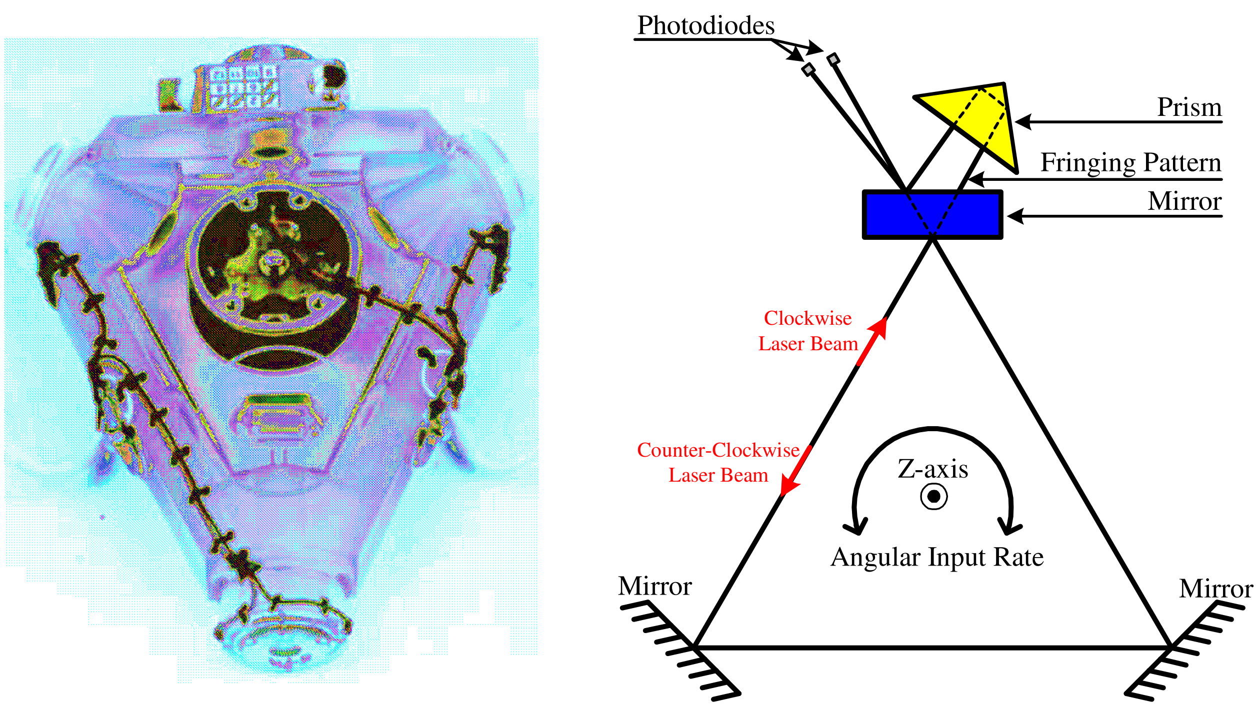


Figure-6.11 Laser gyroscope used by the strap-down INS ***left:[K4-10] right:[K6-20]***

[46] To have accelerometers connected firmly to the airframe is advantageous since it eliminates dynamic errors.
[47] For more on the A/C coordinate system refer to Pages-25 & 26.

- Contains 3 non-movable accelerometers:
  - A_X
  - A_Y
  - A_Z

3) *In addition to velocity and position, INS also provides:*

- TK to fly
- Off-track distance
- Distance between 2 points
- Stores alternate destination positions
- Determines true North direction
- Recalculates ETAs

- **Advantages:**

1) *In General:*
   - INS is a self-contained airborne system that does not need any outside NAV source.
   - Displays in real-time the A/C velocity and position.
   - Operate at all ALT[48].
   - Sometimes GPS is used as an aid to INS in order to correct or attenuate errors.

2) *Stable-Platform INS:*
   - Aligned with the earth coordinate system despite A/C angular motion.
   - Accelerometers and gyros are protected from malfunctioning dude to severe maneuvers since they are not directly connected to the airframe.

3) *Strap-Down INS:*
   - Mechanically simple to realize.
   - Laser gyros are more robust than traditional ones.

- **Disadvantages:**

1) *In General:*
   - *Drift Error*[49] $\approx \pm 0.5$ *kts* $\approx \pm 1$ *km/hr*
   - Accuracy of velocity and position degrade[50] w.r.t. time.

---

[48] Since INS does not depend on GND stations it could operate at all possible ALTs. It's not limited by height.
[49] This error is valid provided no GPS support is available to the INS. In fact, the error is mostly manifested due to the gyro and the integrator used within the INS system.
[50] This is quite obvious since after all INS is a self-contained DR system; i.e. it always depends on the previous result.

- Computational errors:
  - *Round-off and truncation*
  - *Approximation used to simplify calculation algorithms*

- Errors generated by non-orthogonality of accelerometers.

- Vibration and thermal variation may cause flaws in information data.

- INS is an expensive[51] technology.

2) *Stable-Platform INS:*
   - Mechanically more complicated to realize.

   - Errors generated by non-orthogonality of gyros.

   - Gyros may suffer from EMI.

3) *Strap-Down INS:*
   - NAV accuracy is highly dependant on the A/C maneuver, given that the accelerometers and gyros are directly connected to the airframe.

   - Computationally demanding:
     - *Convert* $\vec{a}$ from A/C coordinates to earth coordinates.
     - Then perform DR to get velocity and position.

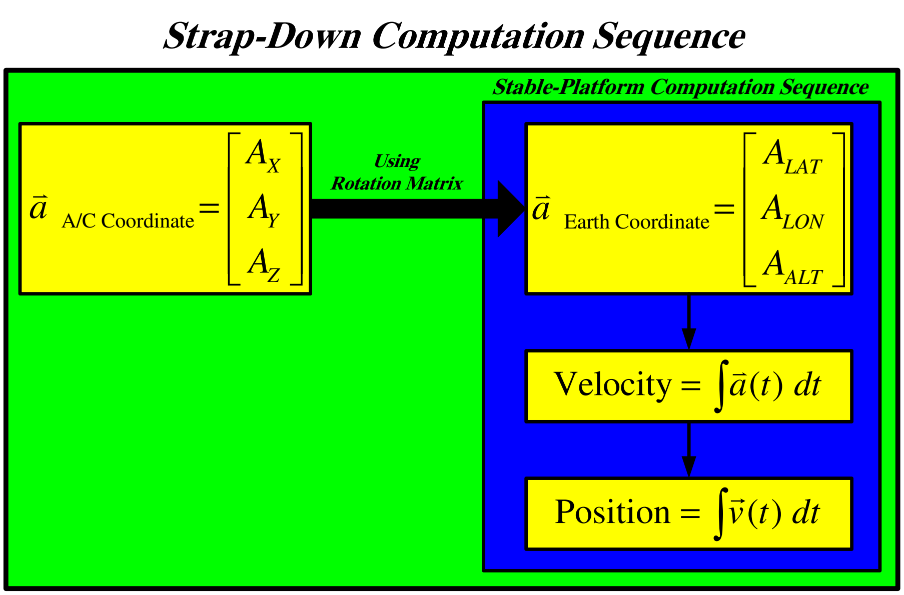


Figure-6.12 Computation sequence in stable-platform and strap-down INS

- **Future:** The combination of INS and GPS is great since one completes the other. In other words, GPS can calibrate the INS drift error, while INS attitude data can aid GPS.

[51] Prices vary from $50,000 to $120,000 US.

6.4 Doppler Navigation System – DNS

- **Principle:** Provides A/C velocity (3D) and position fix (3D). This system is primarily used for MIL purposes requiring high-speed low-altitude flights. First, the A/C velocity is obtained using the Doppler radar, then the information is inputted[52] to a NAV computer so that the position fix can be calculated. Also, similar to INS, this technology is a self-contained DR system and therefore, does not depend on any outside source.

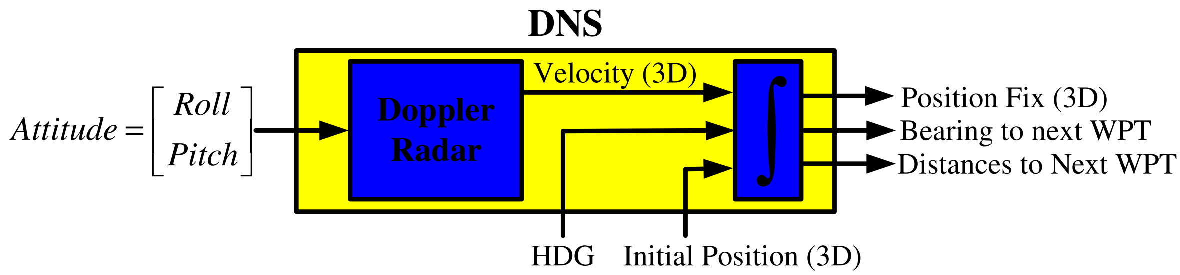


Figure-6.13 DNS

- **In the A/C:**

1) *Tx-Rx: DNS radar system.*

2) *Frequency: SHF*
   - In precipitations: *8.8 – 9.8 GHz*
   - Otherwise: *13.25 – 13.40 GHz*

3) *A/C Doppler radar transmits[53] a beam to GND.*

4) *The beam is reflected and observed at the A/C Rx with velocity information.*

5) *Velocity is then integrated to obtain position.*

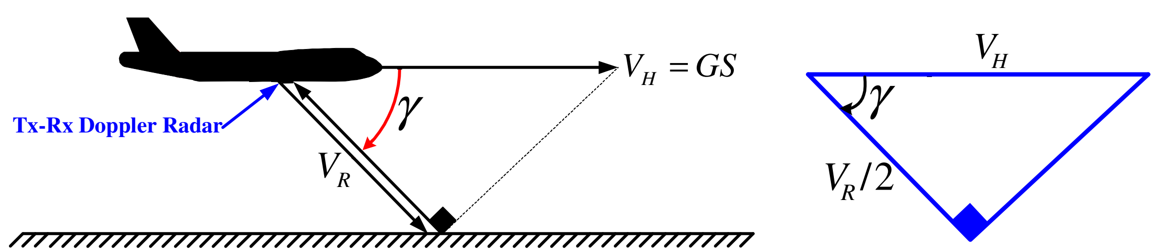


Figure-6.14 Example illustrating calculation of GS using DNS provided A/C is flying straight *[K3-21]*

V_H : A/C Horizontal Velocity Component (i.e. GS) [m/s].

V_R : Relative Velocity Between Tx-Rx [m/s].

ν : Doppler Frequency Shift [Hz].

γ : Angle between V_H and Beam [degrees].

c : Speed of Light $[3\times10^8 \text{m/s}]$.

λ : Wavelength of Transmitted Beam [m].

f : Frequency of Transmitted Beam [Hz].

[52] Notice that the HDG, which is provided either by a magnetic compass or a gyro, is also feed to the integrator.
[53] In fact, there should be a minimum of 3 beams that are transmitted in order to observe a 3D velocity and position fix.

1:	$c = \lambda f \quad \text{or} \quad \lambda = \dfrac{c}{f}$
2:	$V_R = \lambda \nu = \dfrac{c\nu}{f}$
3:	$\cos(\gamma) = \dfrac{adj}{hyp} = \dfrac{V_R/2}{V_H} = \dfrac{V_R}{2V_H} \quad \text{or} \quad V_R = 2V_H \cos(\gamma) = \dfrac{c\nu}{f}$
4:	$V_H\big\vert_{\text{m/s}} = \dfrac{c\nu}{2f\cos(\gamma)} = \dfrac{3\times10^8\nu}{2f\cos(\gamma)} = \dfrac{1.5\times10^8\nu}{f\cos(\gamma)}[\text{m/s}]$
5:	$1[\text{km}] = 1000[\text{m}]$ $1[\text{hr}] = 3600[\text{s}]$ $1[\text{m/s}] = 3.6[\text{km/hr}] = \dfrac{3.6}{1.852}[\text{kts}] = 1.944[\text{kts}]$
6:	$V_H\big\vert_{\text{km/hr}} = \dfrac{1.5\times10^8\times3.6\nu}{f\cos(\gamma)} = \dfrac{5.4\times10^8\nu}{f\cos(\gamma)}[\text{km/hr}]$ $V_H\big\vert_{\text{kts}} = \dfrac{1.5\times10^8\times1.944\nu}{f\cos(\gamma)} = \dfrac{2.916\times10^8\nu}{f\cos(\gamma)}[\text{kts}]$

(6.1)

- **Advantages:**

  1) *DNS is a self-contained airborne system that does not need any outside NAV source.*

  2) *DNS operates over land and water.*

  3) *Average velocity information is extremely accurate.*

  4) *A/C Tx-Rx is light, small, and cheap since it requires a small amount of power for operation.*

  5) *Sometimes a combination of INS-DNS is used to obtain more accurate readings since one technology could correct the other due to the fact that:*
     - ❖ INS will generate a short-term velocity error
     - ❖ DNS will generate a long-term velocity error

- **Disadvantages:**

  1) *Errors:*
     - ❖ *GS Error* $\approx 0.25\% \approx \pm 0.0025 \times V_H$ *kts*
     - ❖ *DA Error* $\approx 0.25\% \approx \pm 0.0025 \times \delta$ *degrees*
     - ❖ *Overall*[54] *System Error* $\approx 0.50\%$

  2) *3D velocities are first obtained in A/C coordinates and then transformed to earth coordinate and therefore calculation errors will be present.*

[54] Here we take into account all possible sources of error including HDG error.

3) *DNS performance is diminished in extreme conditions of rain.*

4) *While operation over water, accuracy is degraded due to:*
   - Water motion
   - Complete smoothness of water surface

- **Future:** GPS is more accurate than DNS; however, DNS should remain in operation for special MIL applications.

6.5 Global Positioning System – GPS

- **Principle:** Provides A/C position fix (3D). This technology is without any dought the most precise system used in NAV by CIV and MIL A/C. To understand why, we first need to realize that generally there exist a tradeoff between position fix accuracy and the coverage area in systems seen thus far. In other words, we cannot have the best of both worlds. However, we know for a fact that SATs operate at the UHF band (i.e. high Freq), and hence accurate position fix reading. As for ensuring a large and excellent coverage area we must place the GPS Transponder (i.e. SAT) faraway in outer space at roughly *20,000 km* form the earth surface, and not on the GND. As a result, GPS[55] becomes an exceptional NAV tool ever invented due primarily to its accurate position fix and large coverage area.

Frequency	Position Fix	Coverage Area
Low (e.g. OMEGA)	Not Accurate	Large
High (e.g. VOR)	Accurate	Small

Figure-6.15 General tradeoff that exists between NAVAID systems

- **Timeline:**

1) *1963:* The concept of GPS is born in a project study by Dr. Ivan Getting of The Aerospace Corporation and Col. Dr. Brad Parkinson of the US Air Force.

2) *1971:* The L_2 frequency concept is added to the GPS project to aid in the correction brought by the ionosphere layer variation.

3) *1973-12-17:* Proposal for the GPS is approved by the Defense System Acquisition and Review Council (DSARC).

4) *1974-06:* Rockwell International[56] is selected as the SAT contractor for the GPS program.

5) *1978-02-22:* First GPS SAT is launched by the US DoD for MIL use.

[55] GPS was initially known as Navigation System with Timing And Ranging (NAVSTAR) by the US Department of Defense (DoD). Since NAVSTAR and GPS are similar terms, they could be used interchangeably.
[56] In December-1996 Rockwell International was acquired by Boeing.

6) *1981-12-18:* Block-I SAT is lost due to a launch failure.

7) *1983-09-16:* US President Ronald Reagan declassifies GPS from purely MIL to being a public project. This decision was made because the Soviet Union shot down a CIV Korean A/C after accidentally entering into Soviet airspace on *1983-09-01*.

8) *1986-01-28:* Space shuttle Challenger explodes during launch. This caused a 2-year delay in the deployment of Block-II GPS, since this vehicle was planned to transport SATs to outer space.

9) *1989-02:* US Coast Guard[57], part of the Department of Transportation (DoT), assumes full responsibility of the GPS program for CIV use.

10) *1990-03-25:* DoD deliberately activates the Selective Availability (SA) in order to degrade the position accuracy for CIV GPS w.r.t. MIL.

11) *1990-08:* GPS SA is turned off during the Persian Gulf War since not enough P(Y) Rx were available; MIL personnel had no choice but to use CIV GPS Rx. All together *9,000* GPS Rx were used during Operation Desert Storm.

12) *1991-07-01:* SA is reactivated after the end of the Persian Gulf War.

13) *1991-09-05:* US decided to make GPS available to the international community free of charge upon its completion.

14) *1995-04-27:* US Air Force Space Command (USAFSC) declares the 24 SAT GPS constellation fully operational.

15) *1997-01-17:* The First of the Block-IIR SATs is lost due to a launch failure.

16) *2000-05-01:* SA is turned off due to a presidential directive by US president Bill Clinton[58] signed in March-1996. Accuracy changed from *100 m* to *10 – 15 m* for CIVs.

- **Position Fix:** To obtain a **2D** position fix we need at least **3 SATs**. Whereas for a **3D** fix a minimum of **4 SATs** are required. Logically speaking, this does not make any sense[59] because it goes without saying that for a least position fix calculation, the size of the dimension and SAT must be equal. Technically speaking, that is right; however, from a practical or cost effective approach we will always require an extra SAT. The reasoning below will help us understand why:

$$Number\ of\ Satellites\ =\ Number\ of\ Dimensions + 1 \tag{6.2}$$

1) *SAT operate at the UHF band ∴ Signal is an LOS Wave ∴ Wave travels at the speed of light*

[57] US Coast Guard Navigation Center: ***www.navcen.uscg.gov***
[58] Statement by US President Bill Clinton on setting SA to zero: ***www.ostp.gov/html/0053_2.html***
[59] It would make some sense from a redundancy perspective, but not otherwise.

2) *Speed of light* $= c = 3 \times 10^8 = 0.3 \times 10^9 = 0.3 / 10^{-9}$ *[m/s] = 0.3 [m/nsec]*

3) *From the speed of light transformation above, we obtain the following important correspondence*[60]*:*

$$\{ \text{Timing Error} = \pm 1 \text{ [nsec]} \} \quad \equiv \quad \{ \text{Position Fix Error} = \pm 0.3 \text{ [m]} \} \tag{6.3}$$

4) *All this, to say that we need powerful clocks to measure the time*[61] *that it takes for a signal to go from the SAT to the GPS-Rx.*

5) *The most precise clocks available today are known as atomic clocks*[62]*. They exist in 2 types with clock frequency of 10.23 MHz*[63]*:*

- Cesium (Cs) Atomic Clock:
  - Error Rate: *1 [sec] every 1,000,000 [years] ≡ 0.000 001 [sec/year]*
  - Price: *$25,000 – $50,000 US*

- Rubidium (Rb) Atomic Clock:
  - Error Rate: *1 [sec] every 1,000 [years] ≡ 0.001 [sec/year]*
  - Price: *$1,000 – $1,500 US*

6) *To measure the time the signal travels from SAT to Rx would mean that each of these HW must be equipped with an atomic clock. In fact, all GPS SAT have Cs and/or Rb clocks; however, most GPS-Rx have an ordinary quartz timer due to its low-cost w.r.t. an atomic clock. Hence, the measured signal time would not be as accurate as desired, which eventually maps to a vague position fix.*

i: Satellite Number.

c: Speed of light $\left[c=3\times10^8 \text{m/s}\right]$.

T_i: Accurate time it take a signal to travel from SAT to the GPS-Rx $[\text{sec}]$.

$\tilde{T}_i$: Inaccurate time it take a signal to travel from SAT to the GPS-Rx $[\text{sec}]$.

ΔT: Time factor of inaccuracy $[\text{sec}]$.

R_i: Accurate range between SAT and the GPS-Rx $[\text{m}]$.

$\tilde{R}_i$: Inaccurate range between SAT and the GPS-Rx $[\text{m}]$.

ΔR: Range factor of inaccuracy $[\text{m}]$.

[60] Correspondence [≡ or ↔] is not the same thing as equivalence [=]; correspondence is derived from a ratio as in the case of the speed of light.

[61] SATs time are regulated and synchronized by the US Naval Observatory (USNO) master clock located in Washington D.C.: ***http://tycho.usno.navy.mil/cgi-bin/anim***

[62] The name atomic clock could be misleading, in the sense that me might think that it uses atomic or nuclear energy or that it is radioactive; it's actually far from that. Atomic clocks, as in traditional clocks, keep track of time through oscillation generated by a mass-spring model system. The major difference here is that oscillation occurs between the nucleus [proton: positive charge | neutron: no charge] of an atom and the surrounding electrons [negative charge].

[63] We need to realize here that a SAT clock would appear to run faster by a factor of 38 μsec / day w.r.t. a clock on earth even if they were initially synchronized. This effect is in principle due to Albert Einstein theory of relativity known as time dilation. Therefore, to make the SAT clock appear to run at the same rate as the one on earth an offset is introduced to the SAT clock: *10.23 – 0.000 000 004 57 = 10.229 999 995 43 MHz.*

$X_{S\text{-i}}$: Satellite X-axis component $[\mathrm{m}]$.
$Y_{S\text{-i}}$: Satellite Y-axis component $[\mathrm{m}]$.
$Z_{S\text{-i}}$: Satellite Z-axis component $[\mathrm{m}]$.
$X_{A/C}$: A/C X-axis component $[\mathrm{m}]$.
$Y_{A/C}$: A/C Y-axis component $[\mathrm{m}]$.
$Z_{A/C}$: A/C Z-axis component $[\mathrm{m}]$.

1:	$i = 1,2,3$	Logically speaking 3 SATs are required for a 3D position fix.
2:	$\tilde{T}_i$	Measure the time that it takes for a signal to go from a SAT to a GPS-Rx. This measured time is obviously inaccurate since the Rx does not have an atomic clock.
3:	$T_i < \tilde{T}_i$ $\therefore$ $T_i = \tilde{T}_i - \Delta T$	The measured inaccurate time is for sure greater than the actual time by a factor of say ΔT.
4:	$R_i = cT_i = c\left(\tilde{T}_i - \Delta T\right) = c\tilde{T}_i - c\Delta T$ $\therefore$ $R_i = \tilde{R}_i - \Delta R$	The actual distance between the SAT and the observer is nothing else than the inaccurate range minus some factor ΔR.
5:	$\left\Vert \begin{bmatrix} X_{S\text{-}i} \\ Y_{S\text{-i}} \\ Z_{S\text{-}i} \end{bmatrix} - \begin{bmatrix} X_{A/C} \\ Y_{A/C} \\ Z_{A/C} \end{bmatrix} \right\Vert = \left\Vert \begin{matrix} X_{S\text{-}i} - X_{A/C} \\ Y_{S\text{-i}} - Y_{A/C} \\ Z_{S\text{-}i} - Z_{A/C} \end{matrix} \right\Vert$ = $\sqrt{\left(X_{S\text{-}i} - X_{A/C}\right)^2 + \left(Y_{S\text{-}i} - Y_{A/C}\right)^2 + \left(Z_{S\text{-}i} - Z_{A/C}\right)^2}$ = $R_i = \tilde{R}_i - \Delta R = c\tilde{T}_i - \Delta R$ $\therefore$ $\sqrt{\left(X_{S\text{-}i} - X_{A/C}\right)^2 + \left(Y_{S\text{-}i} - Y_{A/C}\right)^2 + \left(Z_{S\text{-}i} - Z_{A/C}\right)^2} = c\tilde{T}_i - \Delta R$	We know the SAT position $\left(X_{S\text{-}i}, Y_{S\text{-}i}, Z_{S\text{-}i}\right)$, we also know the inaccurate time $\tilde{T}_i$ and the speed of light c. What we want at this moment is to get the A/C position, namely $\left(X_{A/C}, Y_{A/C}, Z_{A/C}\right)$. However, we have another unknown ΔR; this means that the number of unknowns is actually 4 and not 3. To solve for 4 unknowns, we must have 4 equations, i.e. we need data from 4 SATs and not 3. $\therefore\ i = 1,2,3,4$

(6.4)

Satellite #1:	$\sqrt{\left(X_{S\text{-}1}-X_{A/C}\right)^2+\left(Y_{S\text{-}1}-Y_{A/C}\right)^2+\left(Z_{S\text{-}1}-Z_{A/C}\right)^2}=c\tilde{T}_1-\Delta R$	(6.5)
Satellite #2:	$\sqrt{\left(X_{S\text{-}2}-X_{A/C}\right)^2+\left(Y_{S\text{-}2}-Y_{A/C}\right)^2+\left(Z_{S\text{-}2}-Z_{A/C}\right)^2}=c\tilde{T}_2-\Delta R$	
Satellite #3:	$\sqrt{\left(X_{S\text{-}3}-X_{A/C}\right)^2+\left(Y_{S\text{-}3}-Y_{A/C}\right)^2+\left(Z_{S\text{-}3}-Z_{A/C}\right)^2}=c\tilde{T}_3-\Delta R$	
Satellite #4:	$\sqrt{\left(X_{S\text{-}4}-X_{A/C}\right)^2+\left(Y_{S\text{-}4}-Y_{A/C}\right)^2+\left(Z_{S\text{-}4}-Z_{A/C}\right)^2}=c\tilde{T}_4-\Delta R$	

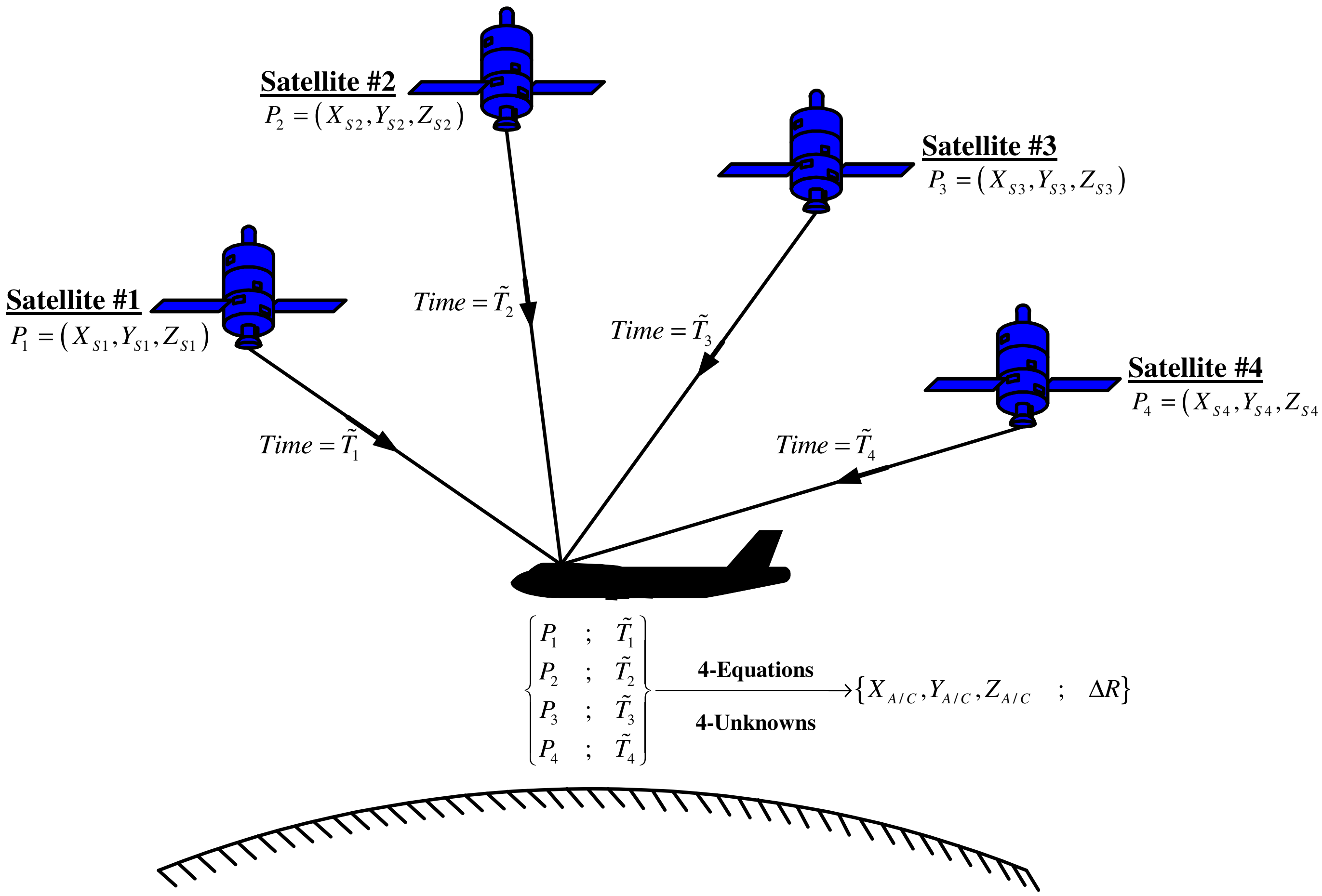


Figure-6.16 A/C position fix using GPS *[K6-21]*

- **Transformation:** The Earth Centered Earth Fixed (ECEF) Cartesian coordinate system or *{X,Y,Z}* explained above is quite useful since it simplifies the position fix calculation. However, it does not give us a sense of where we are geographically w.r.t. earth using familiar terms such as *{LAT,LON,ALT}* of the geodetic system. Also, as far as the transformation is concerned, it is highly dependent on two constants representing the equatorial (*a*) and polar (*b*) radii. Several interpretations of *a* and *b* exist; however, the GPS technology uses the World Geodetic System of 1984 (WGS-84) datum as shown below:

a : Earth Equatorial Radius (a.k.a. semi-major axis) $[6{,}378{,}137 \text{ m}]$

b : Earth Polar Radius (a.k.a. semi-minor axis) $[6{,}356{,}752.3142 \text{ m}]$

f : Flattening of Ellipsoid $\left[(a-b)/a = 0.003352810664\right]$

e : First Eccentricity of Ellipsoid $\left[\sqrt{f(2-f)} = 0.081819190842622\right]$

e' : Second Eccentricity of Ellipsoid $\left[\sqrt{a^2-b^2}/b = 0.082094437949696\right]$

X : X-axis Component $[\text{m}]$

Y : Y-axis Component $[\text{m}]$

Z : Z-axis Component $[\text{m}]$

LAT : Latitude $[\text{degrees}]$

LON : Longitude $[\text{degrees}]$

ALT : Altitude $[\text{m}]$

v : Radius of Curvature

P : Temporary storage

θ: Temporary storage

{X , Y , Z} ⟶ {LAT , LON , ALT}[64]

1 :	$P = \sqrt{X^2 + Y^2}$
2 :	$\theta = \arctan\left(\dfrac{Z \times a}{P \times b}\right)$
3 :	$LAT = \arctan\left(\dfrac{Z + e'^2 b \sin^3(\theta)}{P - e^2 a \cos^3(\theta)}\right)$
4 :	$LON = 2 \times \arctan\left(\dfrac{Y}{X}\right)$
5 :	$v = \dfrac{a}{\sqrt{1 - e^2 \sin^2(LAT)}}$
6 :	$ALT = \dfrac{P}{\cos(LAT)} - v$

(6.6)

[64] A Matlab code for this transformation is available in Appendix D. Mathematically speaking, this conversion will generate an error in the centimeter range (*1 cm = 0.00001 km*) provided *ALT < 1,000 km*. This should not be an issue since typical commercial A/C such as a Boeing-747-400 has a maximum ALT of roughly *12 km*.

{X , Y , Z} ⟵ {LAT , LON , ALT}[65]

1:	$v = \dfrac{a}{\sqrt{1-e^2\sin^2(LAT)}}$	(6.7)
2:	$X = (v + ALT)\cos(LAT)\cos(LON)$	
3:	$Y = (v + ALT)\cos(LAT)\sin(LON)$	
4:	$Z = \left(v\left(1-e^2\right) + ALT\right)\sin(LAT)$	

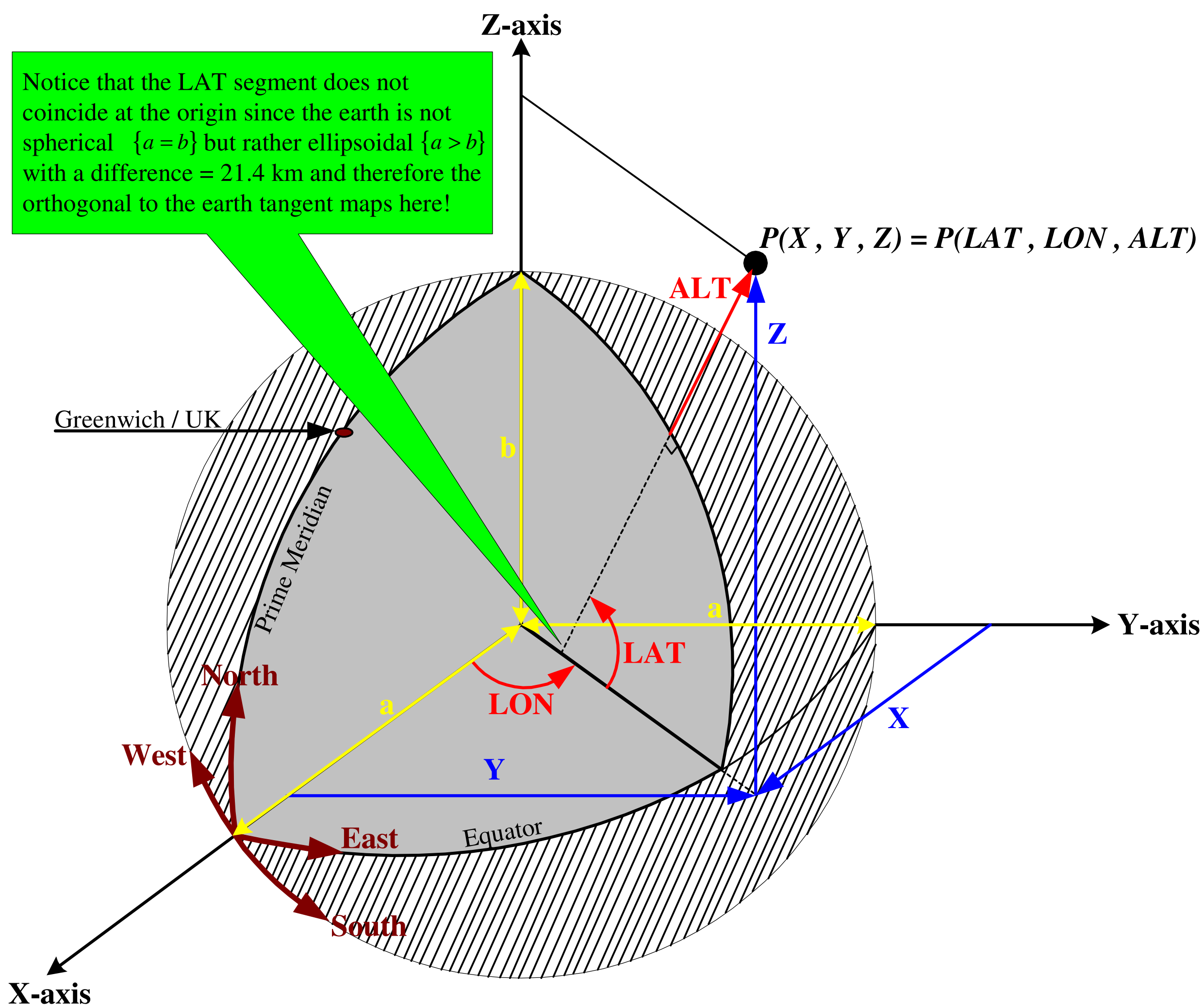


Figure-6.17 Graphical definition of *{X,Y,Z}* and *{LAT,LON,ALT} [K6-22]*

65 A Matlab code for this transformation is available in Appendix E.

- **<u>On the GND:</u>** ***[a.k.a. Control Segment]***

    1) *Rx-Tx: Monitor Stations, Master control Station, and GND Antennas.*

    2) *Monitor Stations:*
        - ❖ Number worldwide: *6*

        - ❖ Monitor stations receives NAV signals from SATs and then transmits it to the Master control station for processing.

    3) *Master Control Station:*
        - ❖ Number worldwide: *1*

        - ❖ Once or sometimes twice a day, master control determines any NAV adjustments or updates needed and then forwards it to the GND antennas.

        - ❖ These updates are for:
            - ➢ *Orbital info (i.e. SAT location within the orbit)*
            - ➢ *Clock synchronization*
            - ➢ *Status of the ionosphere layer*

    4) *GND Antennas:*
        - ❖ Number worldwide: *4*

        - ❖ Receives updates from the master control station and emits signals to SATs.

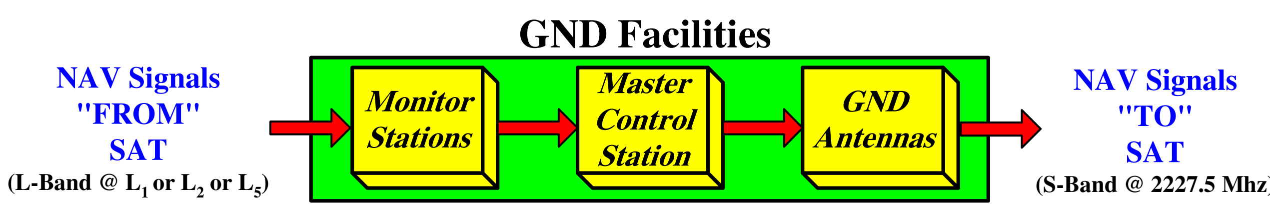


Figure-6.18 GPS GND facilities

LOCATION	Monitor Stations	Master Control Station	GND Antennas
US / Colorado Springs Schriever Air Force Base	✓	✓	
US / Florida Cape Canaveral	✓		✓
US / Hawaii (Pacific Ocean)	✓		
US / Kwajalein Atoll (Pacific Ocean)	✓		✓
UK / Ascension Island (Atlantic Ocean)	✓		✓
UK / Diego Garcia (Indian Ocean)	✓		✓

Figure-6.19 Tabular location of GPS GND stations

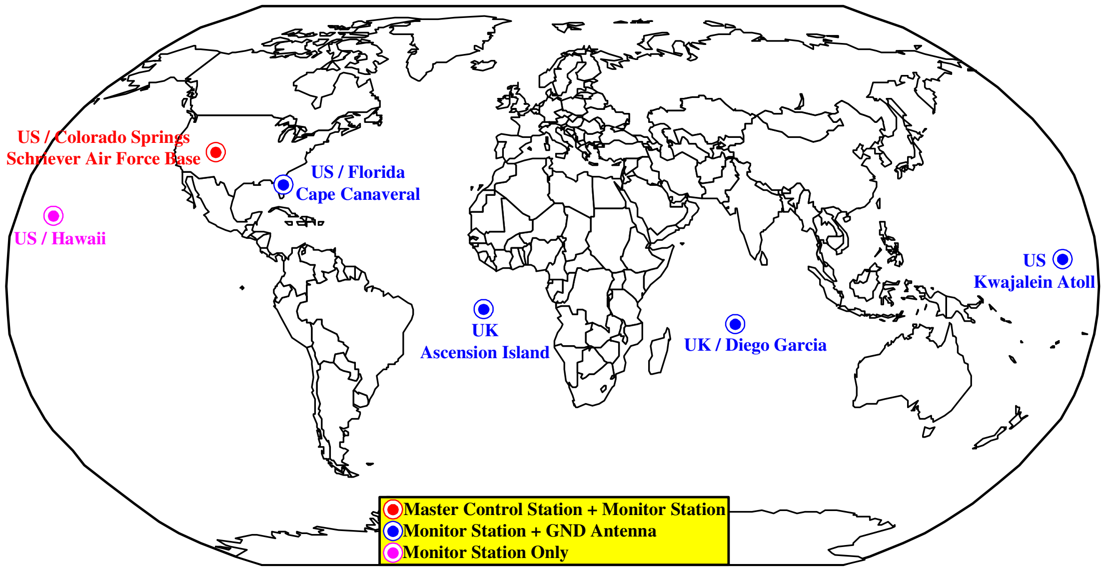


Figure-6.20 Location of GPS GND stations *[K6-23]*

- **<u>In Space:</u>** ***[a.k.a. Space Segment]***

  1) *Tx-Rx: GPS-SAT systems.*

  2) *Frequency: UHF*

     ❖ ***L-Band ≈ 500 – 2000 MHz:*** This band is used in GPS SAT communications.

     ❖ ***L_1 = 1575.42 MHz:*** This Freq is available to CIVs using Course Acquisition (C/A) modulation. It is also available to MIL Rx in two coding known as Precise-Encrypted (P(Y)) and Military-Encrypted (M) modulations. Essentially, the M-code offers a better jamming resistance from enemy w.r.t. P(Y)-code.

     ❖ ***L_2 = 1227.60 MHz:*** This Freq is also available to CIV and MIL Rxs primarily to increase position fix accuracy, to remove errors caused by layer variation of the ionosphere, and to act as a backup frequency.

     ❖ ***L_5 = 1176.45 MHz:*** This Freq is expected to be in action sometime in *2007*. It is specifically reserved for CIV use in the field of commercial aviation with improved accuracy.

     ❖ ***L_3 = 1381.05 MHz:*** This Freq is used by the US DoD for detecting missiles, rockets, nuclear detonations, and other high energy infrared events.

     ❖ ***L_4 = 1841.40 MHz:*** This Freq is understudy for future improvement of GPS.

Code Names		Signal Frequencies		Carrier Frequencies		
		1.023 MHz	10.23 MHz	L_1 = 1575.42 MHz	L_2 = 1227.60 MHz	L_5 = 1176.45 MHz
CIV	C/A	✓		✓		
CIV	L2C	✓			✓	
CIV	L5C		✓			✓
MIL	P(Y)		✓	✓	✓	
MIL	M		✓	✓	✓	

Figure-6.21 GPS frequencies[66] *[K6-24]*

3) *Orbitals[67]:*
    - Planes = *6*
    - Inclination = 55^0
    - Number of Active SATs per Plane = *4*

4) *Position:*
    - SATs ALT above the earth surface = *10,988 nm* ≈ *20,350 km*
    - The position of each SAT is predefined and known w.r.t. time such that a minimum of *5* SATs are in view at all times.

5) *Speed:*
    - Period[68] = *12 hrs*
    - Average SAT Velocity ≈ *11,265 km/hr*

6) *Power:*
    - Sun radiation forms the main source of energy intercepted by solar arrays.
    - Rechargeable batteries are also included onboard SATs to ensure activity during darkness or a solar eclipse.

7) *Atomic Clocks:*
    - Each SAT contains either *3* or *4* atomic clocks. Only one of the clocks is actively used; the others remain on standby in case of an emergency or during maintenance.

8) *Operational SATs:*
    - As of *November-2005*[69] there are *29* operational SATs in outer-space based on *4* generations[70].

---

[66] Signal Freq is the rate of the data (binary); whereas the carrier Freq is the rate at which the data is transmitted from SAT to Rx.
[67] The *6* GPS orbitals are expected to be circular; however, they slightly tend to become elliptical due to a drift from the predefined position mainly caused by the gravitational pull of earth, moon and sun. This will eventually make the travel speed of SATs vary, and hence introduce position fix errors. GND control stations will reposition SATs periodically as will be explained later; also, some GPS-Rxs correct this factor using an offset rate value.
[68] Period stands for the time it takes to go once around earth.
[69] For the latest constellation information refer to: ***ftp://tycho.usno.navy.mil/pub/gps/gpsb2.txt*** ***ftp://tycho.usno.navy.mil/pub/gps/gpstd.txt*** and ***www.navcen.uscg.gov/ftp/gps/status.txt***
[70] In general new SAT will carry improved features while remaining backward compatible.

SAT Generations	Number of SATs	Number of Active Clocks	
		Cs	Rb
Block-II	1	1	0
Block-IIA	15	8	7
Block-IIR	12	0	12
Block-IIR-M	1	0	1

Figure-6.22 Number of operational SATs and active Clocks w.r.t. GPS generations

9) *Active SATs:*
   - ❖ At all times, *24* SATs must remain active to ensure a worldwide coverage. The remaining *5* SATs are there for backup in case an unexpected malfunction occurs or a deliberate shutdown is forced for maintenance.

10) *Coverage Angle:*
   - ❖ SAT Field of View = $2 \times 13.84^0 = 27.68^0 \approx 28^0$

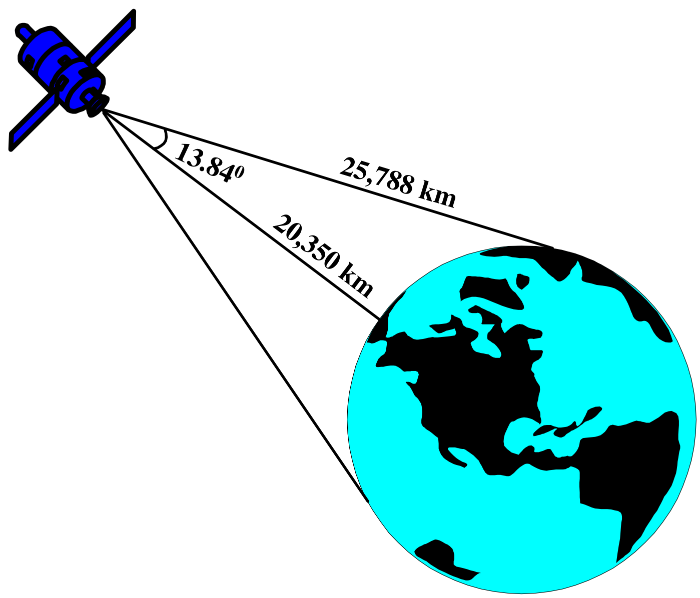


Figure-6.23 Coverage angle of GPS SATs ***[K3-22]***

11) *Typical Maintenance required for each SAT:*

   - ❖ Atomic clocks need to have their beam-tube pumped.
     - ➢ Rate: *Twice a year*
     - ➢ Downtime: *18 hrs*

   - ❖ SATs need to be repositioned to their original predefined location using small onboard rocket boosters.
     - ➢ Rate: *Once a year*
     - ➢ Downtime: *12 hrs*

GPS-I

Block-I

- **First Launch:** Feb-1978
- **Last Launch:** Oct-1985
- **Success:** 10-SATs
- **Failure:** 1-SAT
- **Clocks:** 1-Cs , 2-Rb
- **Solar Power:** 410 watts
- **Batteries:** 3-15 cell NiCd
- **Mass:** 760 kg
- **Design Life:** 5 years
- **MIL:** P(Y) @ L1 , L2
- **By:** Rockwell International [now Boeing]

GPS-II

Block-II

- **First Launch:** Feb-1989
- **Last Launch:** Oct-1990
- **Success:** 9-SATs
- **Failure:** None
- **Clocks:** 2-Cs , 2-Rb
- **Solar Power:** 710 watts
- **Batteries:** 3-15 cell NiCd
- **Mass:** 1660 kg
- **Design Life:** 7.5 years
- **CIV:** C/A @ L1
- **MIL:** P(Y) @ L1 , L2
- **By:** Rockwell International [now Boeing]

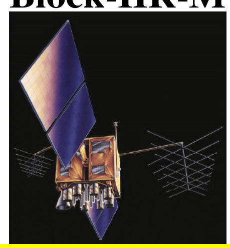
Block-IIA

- **First Launch:** Nov-1990
- **Last Launch:** Nov-1997
- **Success:** 19-SATs
- **Failure:** None
- **Clocks:** 2-Cs , 2-Rb
- **Solar Power:** 710 watts
- **Batteries:** 3-35 cell NiCd
- **Mass:** 1816 kg
- **Design Life:** 7.5 years
- **CIV:** C/A @ L1
- **MIL:** P(Y) @ L1 , L2
- **By:** Rockwell International [now Boeing]

Block-IIR

- **First Launch:** Jan-1997
- **Last Launch:** Nov-2004
- **Success:** 12-SATs
- **Failure:** 1-SAT
- **Clocks:** 3-Rb
- **Solar Power:** 1136 watts
- **Batteries:** 2-NiH_2
- **Mass:** 2032 kg
- **Design Life:** 10 years
- **CIV:** C/A @ L1
- **MIL:** P(Y) @ L1 , L2
- **By:** Lockheed Martin

Block-IIR-M



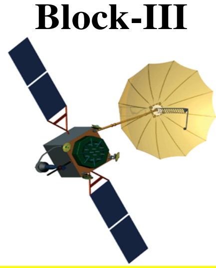
- **First Launch:** Sep-2005
- **Last Launch:** ------------
- **Success:** 1-SAT [so far]
- **Failure:** None [so far]
- **Clocks:** 3-Rb
- **Solar Power:** 1136 watts
- **Batteries:** 2-NiH_2
- **Mass:** 2032 kg
- **Design Life:** 10 years
- **CIV:** C/A @ L1, L2C @ L2
- **MIL:** P(Y) @ L1 , L2; M @ L1 , L2
- **By:** Lockheed Martin

Block-IIF

- **Expected Launch:** 2007
- **Clocks:** ????
- **Solar Power:** 2440 watts
- **Batteries:** ????
- **Mass:** 2900 kg
- **Design Life:** 15 years
- **CIV:** C/A @ L1, L2C @ L2, L5C @ L5
- **MIL:** P(Y) @ L1 , L2; M @ L1 , L2
- **By:** Boeing

GPS-III

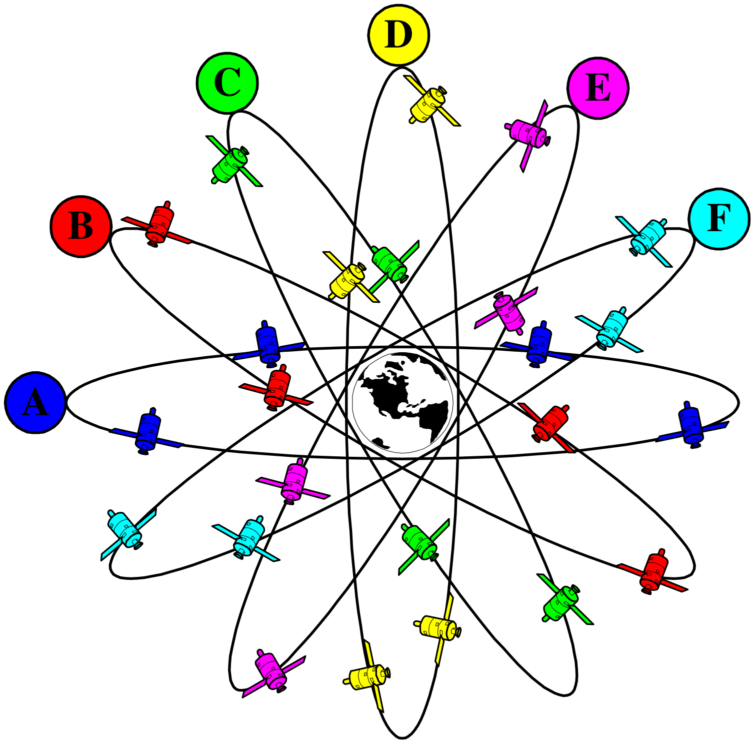
Block-III



- **Expected Launch:** 2013
- **By:** Boeing & Lockheed Martin

NiCd: Nickel Cadmium
NiH_2: Nickel Hydrogen

Figure-6.24 GPS generations *[K5-4]*



Planes	Main Slots				Extra Slots		
	1	2	3	4	5	6	7
A	39	25	38	27	-	-	-
B	56	30	44	35	-	-	-
C	36	33	59	37	-	-	-
D	24	46	45	34	15	53	61
E	51	47	40	54	-	-	-
F	41	26	43	60	29	32	-
Numbers 15 and above represent the Satellite Vehicle Number (SNV) as of NOV-2005							

Figure-6.25 GPS SAT Constellation[71] *left:[K6-25] right:[K6-26]*

12) *Each GPS SAT Transmit 3 Signals:*

- Pseudo-Random Code (PRC)[72]: *Contains SAT ID since each SAT has a unique PRC[73]. Also, the PRC is used to calculate the time it takes a signal to go from SAT to GPS-Rx; and therefore, it is often referred to as time signal.*
- Ephemeris data: *Contains SAT position w.r.t. time.*
- Almanac data: *Contains information about SAT status [healthy or unhealthy].*

- **<u>In the A/C:</u>** ***[a.k.a. User Segment]***

1) *Rx: GPS-Rx system.*

2) *Frequency: UHF*

[71] A list of all GPS SATs launched so far is available in Appendix F.
[72] The signal is called Pseudo-Random, because the bits (bits are binary since it either takes a *1* or a *0*; also a *bit* is sometime called a *chip* and therefore the Freq of a digital signal is commonly referred to as *chipping rate*) appear as digital noise; however, this is not the case since the bit sequences do repeat after a specific time, and hence do carry useful information.
[73] Even if signals are transmitted at the same frequency by different SATs, interference should not be an issue since each signal is unique due to its PRC.

3) *GPS-Rx will observe data form at least 4 SATs in order to solve for the unknowns using the 4-equations of (6.5). It is quite evident that an iterative numerical analysis approach will be used to solve for unknowns due to the nonlinearity of the equations.*

4) *The storage part of the Rx, which is updatable, contains a database with information on:*

- Airspace
- Airports
- NAV facilities
- Etc.

5) *The main purpose of GPS is to calculate A/C position fix; however, other secondary outputs are also made available such as:*

- TAS & HDG
- GS & TK
- WS & WA
- Distance to next WPT and/or to destination
- ETA to next WPT and/or to destination
- Moving map display
- Intensity of each signal received
- Condition of each SAT tracked
- Etc.

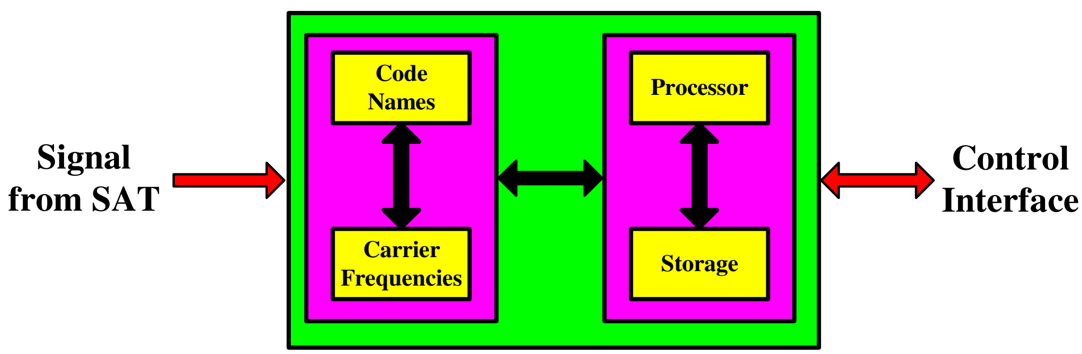


Figure-6.26 GPS-Rx *[K3-23]*

- **Advantages:**

1) *GPS is the most accurate NAV system ever invented.*
2) *GPS provides continuous real-time NAV information.*
3) *GPS is an all-weather system.*
4) *GPS is available 24/7 to the international community.*
5) *GPS is available free of charge without any subscription or license.*
6) *Unlimited users could take advantage of GPS without degradation of the signals quality.*
7) *For MIL activities, GPS could hit the target without causing major collateral damages.*

- **<u>Disadvantages:</u>**

1) *Errors:*

Accuracy	Percentage of Occurance	
	50 %	95 %
Horizontal (i.e. LAT & LON)	4 m	9 m
Vertical (i.e. ALT)	10 m	22 m

Figure-6.27 Typical GPS errors *[K3-24]*

2) *SAT Clock Errors:* SATs use atomic clocks, and they are very precise; however sometimes discrepancies do happen and hence time measurement errors.

3) *Orbital Errors:* SATs should in general maintain their predefined orbital positions, however drifts do occur by gravitational pulls (earth, moon, sun).

4) *Ionosphere and Troposphere Errors:* As signals go from SAT to GPS-Rxs, they pass through the ionosphere and troposphere layers, and when this happens, the signal propagation speed (i.e. speed of light) is slowed down[74]. Note that the slowing rate is variant and non-constant; hence, correction or compensation for this factor is quite complicated.

5) *Rx Noise Errors:* The GPS-Rx will detect the desired NAV signals; however, the signal might be slightly distorted with noise due to the wireless nature of the system.

6) *Multipath Errors:* Ideally we want signals to go straight from SAT to GPS-Rx; however, on occasions the signals get bounced, and the Rx will detect these bounced signals.

Error Sources	GPS Errors [m]
SAT Clock	1.5
Orbital	2.5
Ionosphere	5.0
Troposphere	0.5
Rx Noise	0.3
Multipath	0.6
Total	**10.4**

Figure-6.28 GPS error sources *[K6-27]*

[74] Speed of light remains constant only in vacuum (i.e. a space with no matter and very little gas pressure).

7) *Maintenance:* The cost to maintain the GPS constellation annually, including R&D, is roughly *$ 750,000,000 US*.

8) *Political Uncertainty:* GPS program is managed by the DoD, which means that they may choose to selectively turn off GPS capabilities in certain geographical locations.

- **<u>Future:</u>**

1) *Even though GPS is the most performant global NAV system, there is always place for improvement:*

   - Better accuracy
   - Enhanced performance
   - Added resistance to interference from noise
   - Greater security for the MIL signals
   - Etc.

2) *It is expected that 2 to 4 SATs will be launched every year starting in 2006 to modernize the current SAT constellation.*

3) *More up-to-date GND stations are to be constructed in strategic locations to accommodate for GPS-III*[75]*:*

   - New *Monitor Stations*
   - A fully capable alternate *Master Control Station* located in California's Vandenberg Air Force Base[76].

4) *The GPS market for CIV and commercial applications continues to grow exponentially as predicted by analyst:*

   - Observed in 2003: *$ 16,000,000,000 US*
   - Forecasted by 2010: *$ 68,000,000,000 US*

5) *GPS is doing well now and it must continue as such since important competition still exist or are about to emerge in the near future:*

   - Russian Federation:

     - Name: *Global Navigation Satellite System (GLONASS)*
     - Managed by: *Russian Space Forces part of the Russian Ministry of Defense*
     - First Launch: *1982*
     - Officially Operational: *1993-09-24*
     - Planes = *3*

---

[75] It is being said that GPS-III could achieve an accuracy of *1m* or less.

[76] In the meantime until construction finishes, an interim backup *Master Control Station* exist near Washington D.C.

- Inclination = *120^0*
- Number of SATs per Plane = *8*
- Number of Active SATs = *24*
- SAT ALT = *19,100 km*
- Period = *11 hrs 15 min*

❖ European Union (EU)[77]:

- Name: *GALILEO*
- Managed by: *European Space Agency*
- Expected First Launch: *2006*
- Expected Operations: *2008*
- Planes = *3*
- Inclination = *56^0*
- Expected Number of SATs per Plane = *10 (9 active + 1 operational spare)*
- Expected Number of SATs = *30 (27 active + 3 operational spares)*
- SAT ALT = *23,616 km*
- Period = *14 hrs*

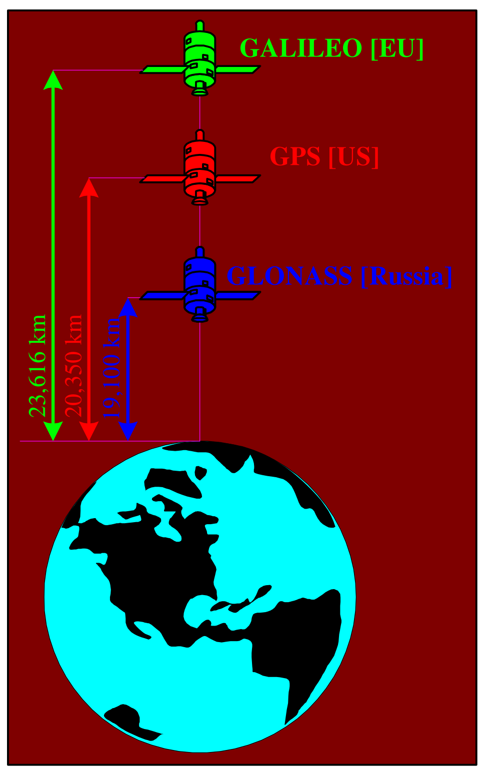


Figure-6.29 GALILEO, GPS, and GLONASS SAT ALTs

[77] Other Non-EU countries have joined the funding of the Galileo program such: *Ukraine*, *Morocco, Saudi Arabia, Israel, India, and China*. Countries that eventually might join the program are: ***Canada***, *Mexico, Brazil, Argentina, Chile, Norway, Pakistan, Malaysia, South Korea, Japan, and Australia*.

Chapter 7

Approach-Landing NAVAIDS

If you have knowledge, let others
light their candle by it.

— Margaret Fuller

7.1 Basics of Approach-Landing – A/L

- **A/L Information:** Essentials required to achieve a successful A/L are:

  1) *Cockpit NAV Instruments*
  2) *ATC data*
  3) *Approach Charts:*
     - ❖ Hardcopy: *i.e. on paper.*
     - ❖ Softcopy: *i.e. on digital NAV Liquid Crystal Displays (LCDs).*

- **A/L Phases:** En-route control transfers responsibility to A/L control to assist in the following *3*-phases:

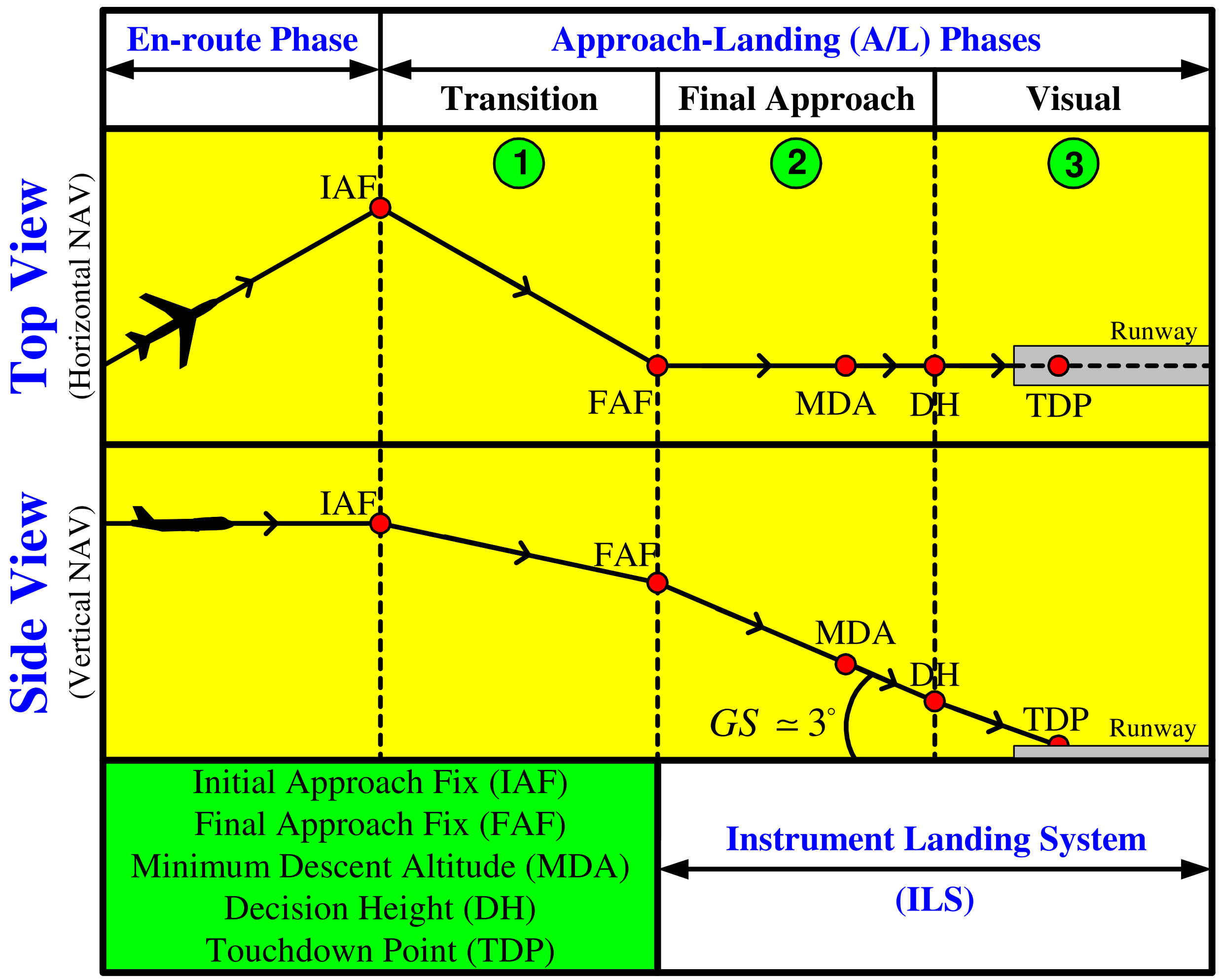


Figure-7.1 A/L phases *[K3-25]*

1) *Transition Phase: A/C leaves the En-route and enters into A/L.*

2) *Final Approach Phase[78]: A/C enters into the ILS Glideslope[79] (GS^0).*

- IFR Precision Approaches:
  - Non-Precision: *A/C does not support vertical NAV*[80].
  - Precision: *A/C does support vertical NAV.*

- Depending on A/C type, decision must be taken at either *MDA* or *DH* on whether to:
  - Continue landing
  - Declare a missed approach and then decide to either:
    - *Go around for another trial*
    - *Go to another airport*

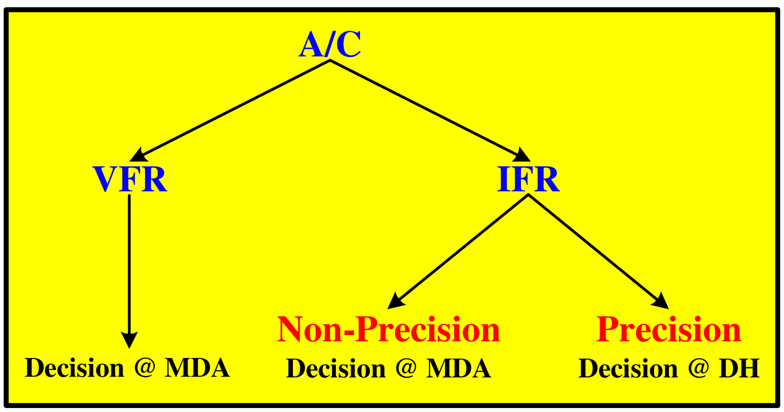


Figure-7.2 MDA/DH decision tree

CAT	DH [ft]	DH [m]	RVR [ft]	RVR [m]
I	200	60	1,800	550
II	100	30	1,200	365
III-A	50	15	700	210
III-B	0→50	0→15	150	45
III-C	0	0	0	0
Runway Category (CAT)	Runway Visibility Range (RVR)			

Figure-7.3 ICAO DH values for IFR precision approaches *[K6-28]*

3) *Visual Phase: From either MDA or DH until TDP, which roughly 1 km, NAV must be performed visually*[81].

[78] To be more specific than what is shown on Figure-7.1, the final approach phase could end at either MDA or DH depending on the A/C flight rule and the precision used.

[79] In this book GS refers to both Ground Speed (velocity) and Glideslope (angle); for the sake of differentiation, Glideslope acronym will be assigned as $GS^0 \approx 3^0$.

[80] In this case, as an example if ILS-GS^0 is not available for landing support, other traditional vertical NAV tools are used such as: Altimeter and VSI as explained in Pages-31 & 32 respectively.

[81] It is quite evident that for a VFR flight, visual NAV is used all along; however even for an IFR flight, the pilot (not the autopilot) must perform this phase visually until TDP.

- **Visual A/L Aids:** Visual runway support during A/L is quite useful for both VFR and IFR A/Cs.

1) *Approach Lighting System – ALS*

❖ Supported A/C: *IFR-precision* [82]

❖ Phases: *DH until TDP*

❖ Color Configurations:
  - ➢ *DH ↔ White*
  - ➢ *Pre-threshold Area ↔ Red & White*
  - ➢ *Runway Threshold ↔ Green*
  - ➢ *Centerline and Edges ↔ White*

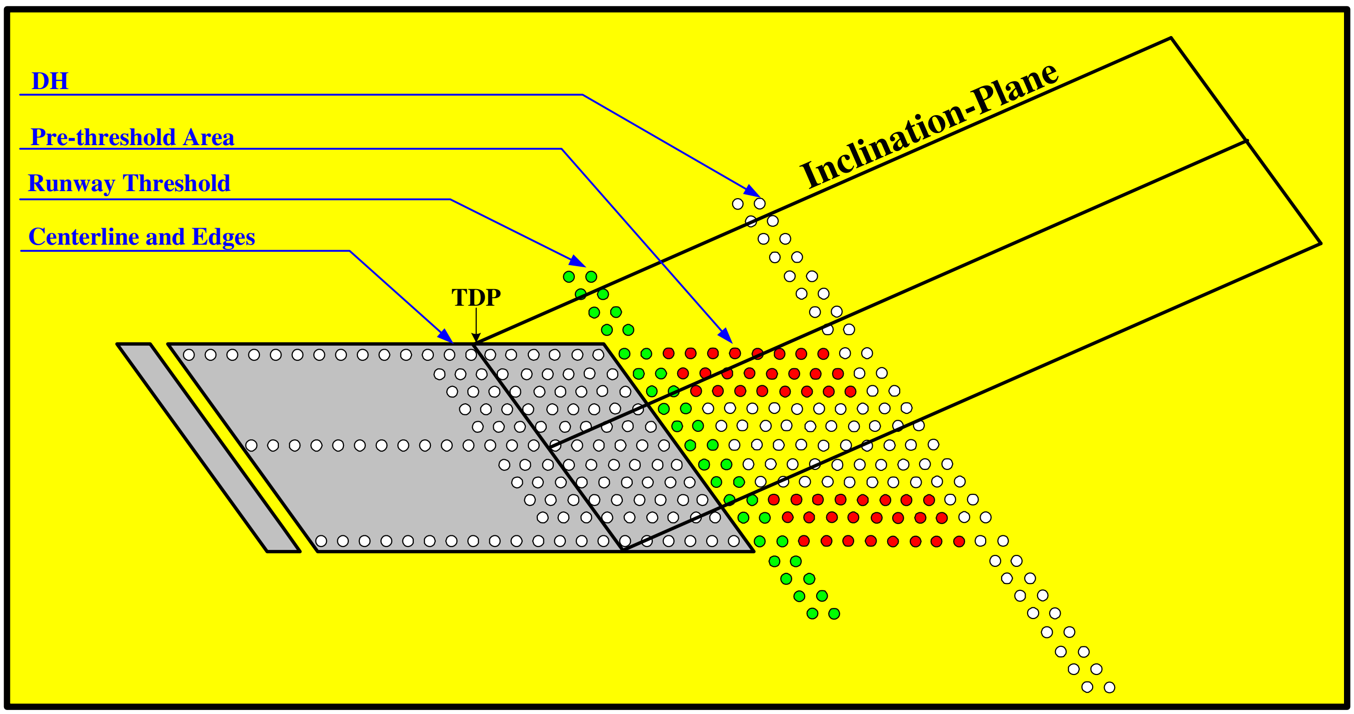


Figure-7.4 ALS *[K3-26]*

2) *Visual Approach Slope Indicator System – VASIS*

❖ Supported A/C: *VFR and IFR-non-precision* [82]

❖ Phases: *MDA until TDP*

❖ Color Configurations:
  - ➢ *Too-high ↔ White & White*
  - ➢ *Normal ↔ Red & White*
  - ➢ *Too-low ↔ Red & Red*

[82] Other type of A/C could still use this system.

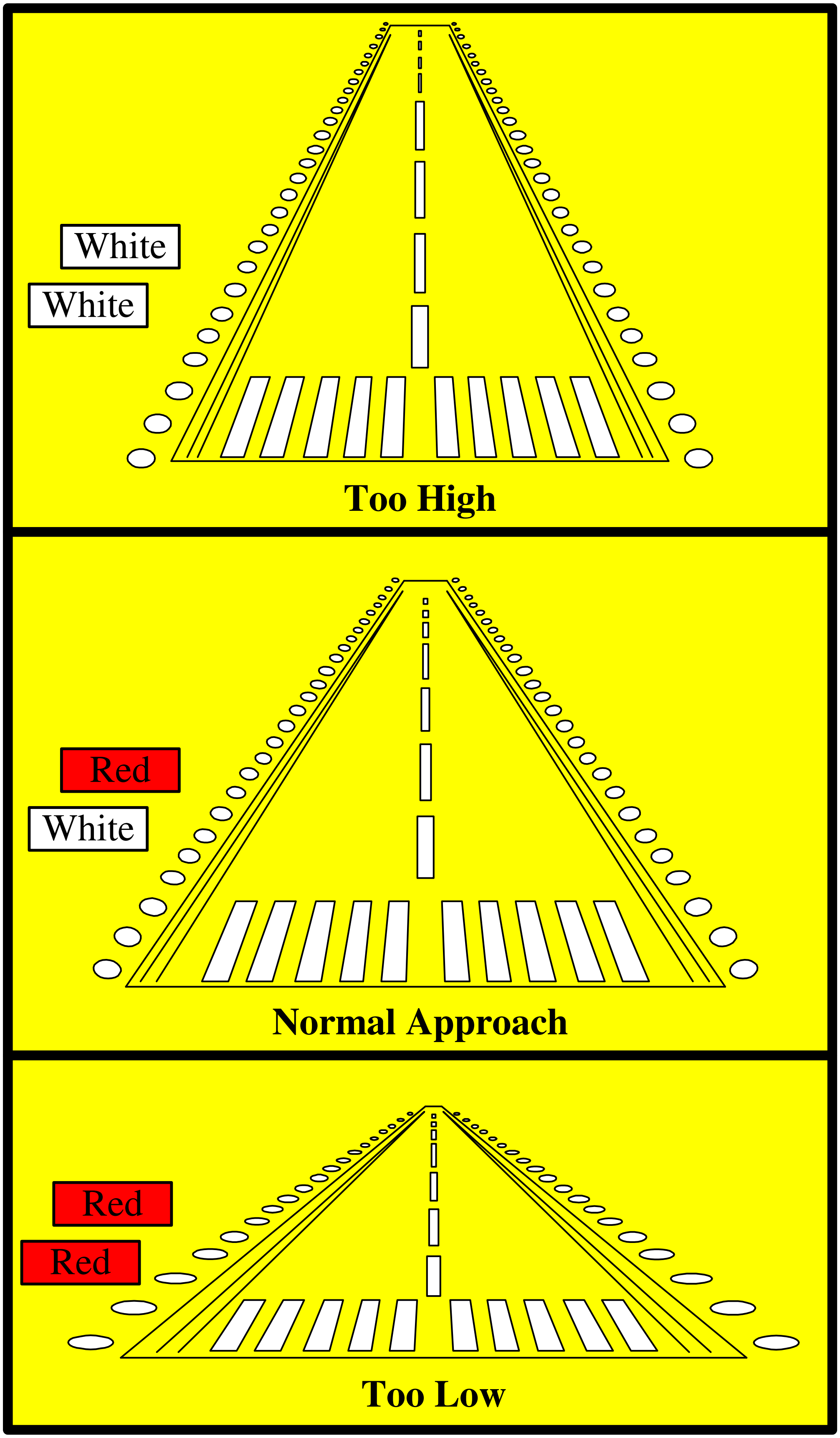


Figure-7.5 VASIS *[K6-29]*

- **Runway Numbering:** Airport runways are numbered for identification. The method used to provide IDs are as follows:

1) *Obtain the runway magnetic bearing from the approaching direction.*

2) *Rounded the bearing to the nearest* 10^0.

3) *Eliminate the last of the 3-digit bearing, the remaining 2-digits form the runway ID.*

4) *To obtain the bearing form the other runway extremity proceed as such:*

$$\left\{ \begin{matrix} Runway\ Bearing \\ from\ one\ extremity \end{matrix} \right\} = \left\{ \begin{matrix} Runway\ Bearing \\ from\ the\ other\ extremity \end{matrix} \right\} \pm 180^0 \tag{7.1}$$

5) *Repeat steps 2 & 3 above to obtain the ID for the other extremity.*

6) *At large airports, there are parallel runways; hence, an extra letter is added to the ID to characterize the position: Left (L), Center (C) and Right (R). These parallel runways could either be* ***double*** *(i.e. 2-runways "L" & "R") or* ***triple*** *(i.e. 3-runways "L" "C" "R")* [83].

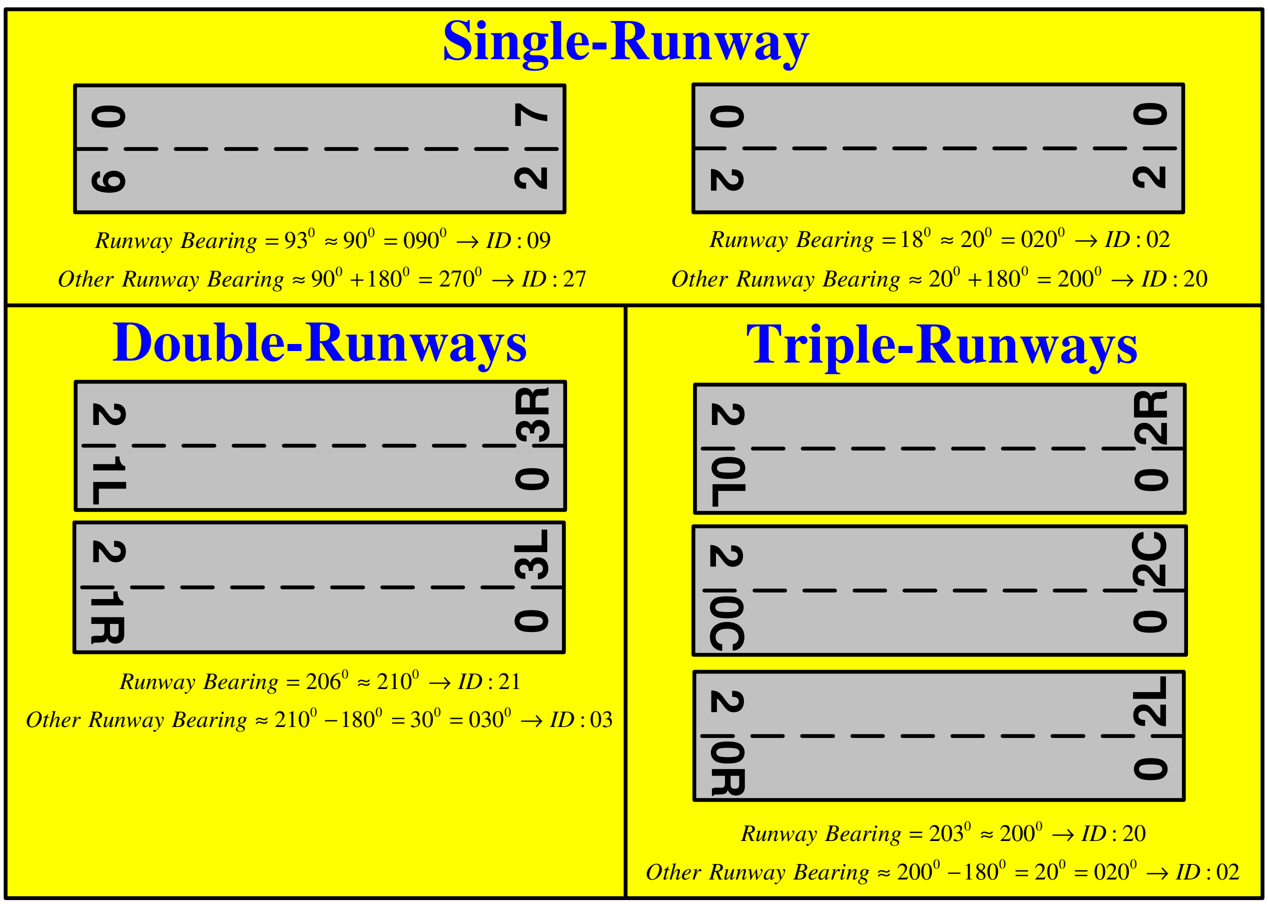


Figure-7.6 Runway Numbering *[K6-30]*

[83] The maximum possible number of runways in a specific direction cannot exceed *3*.

7.2 Instrument Landing System – ILS

- **Principle:** Provides A/C guidance for a straight flight path landing. ILS is used in IFR precision approach A/Cs from FAF until TDP. As for insuring an ideal landing, the system is based on the intersection of the runway centerline, the Localizer (LOC) beam, and the GS^0 beam.

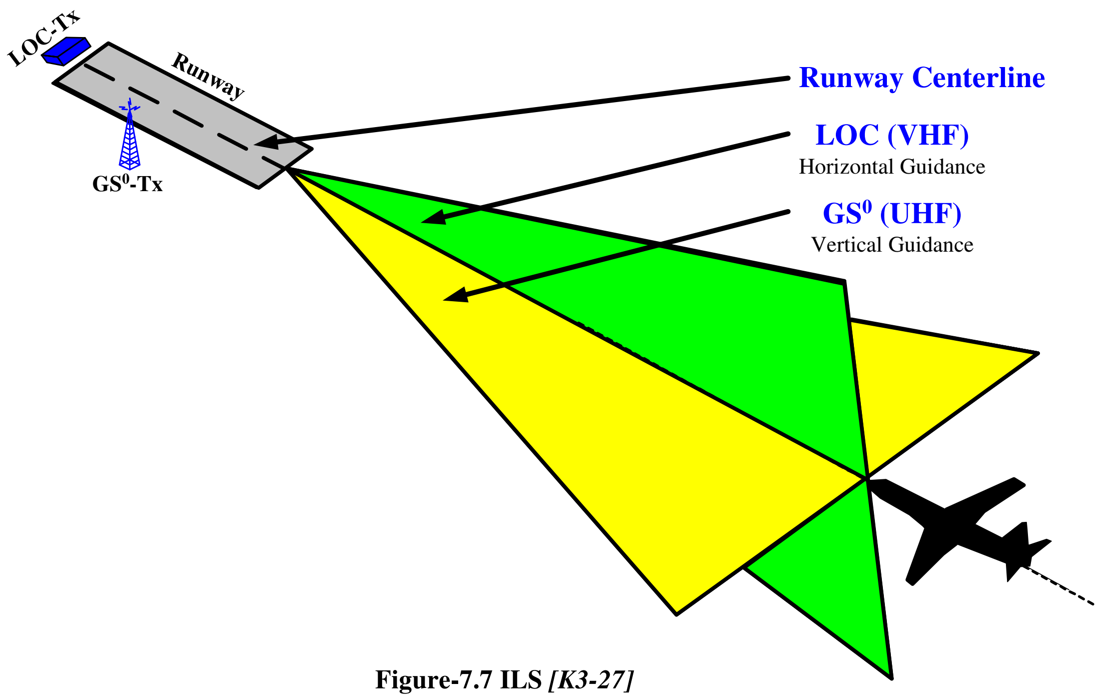


Figure-7.7 ILS ***[K3-27]***

- **On the GND:**

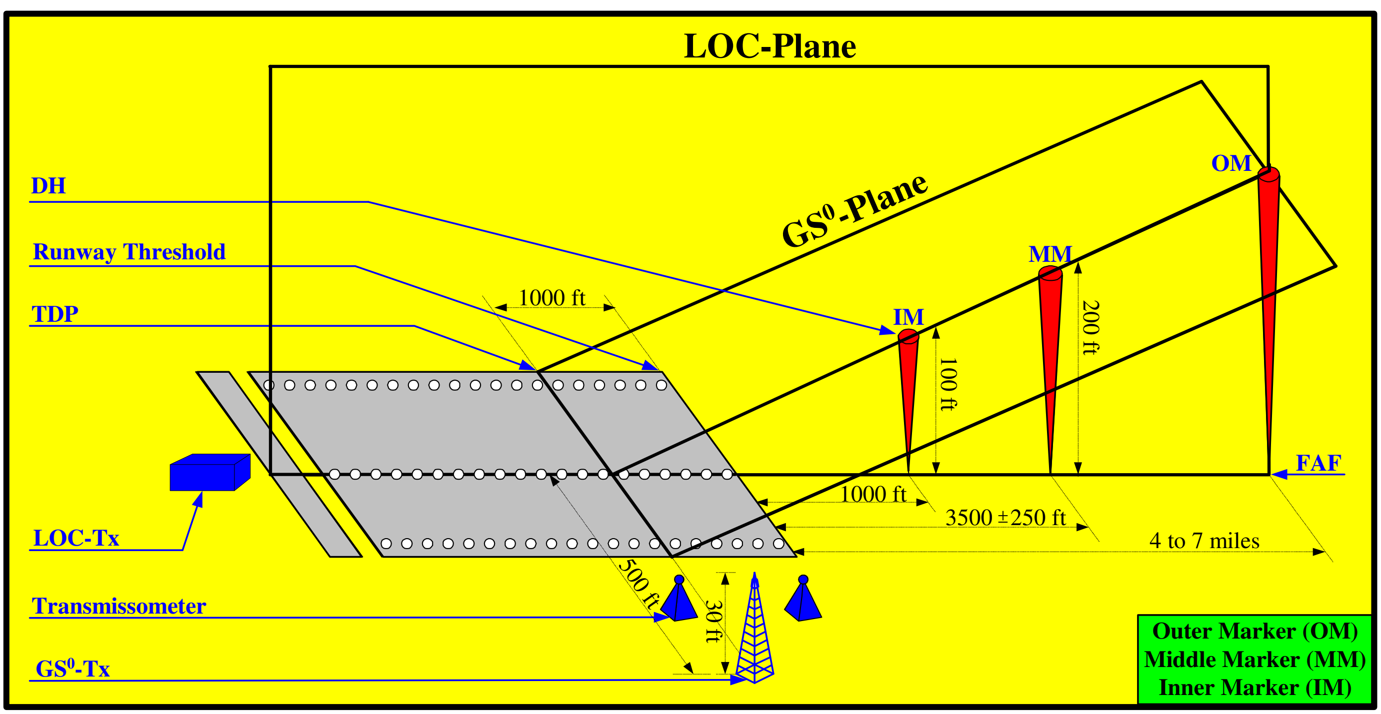


Figure-7.8 ILS CAT-II runway ***[K3-26]***

1) ***LOC–Tx***

- *Function: Provides alignment with runway centerline.*
- *NAV: Horizontal Guidance.*
- *Quantity per runway: 1*
- *Location: At the end of the runway.*
- *Frequency: VHF ≈ 108 – 112 MHz*
  - Number of Channels: *20*
- *Horizontal Range of Operation ≈ 40 km*
- *Deviation from Centerline ≈ ± 2^0 [i.e. 4^0]*

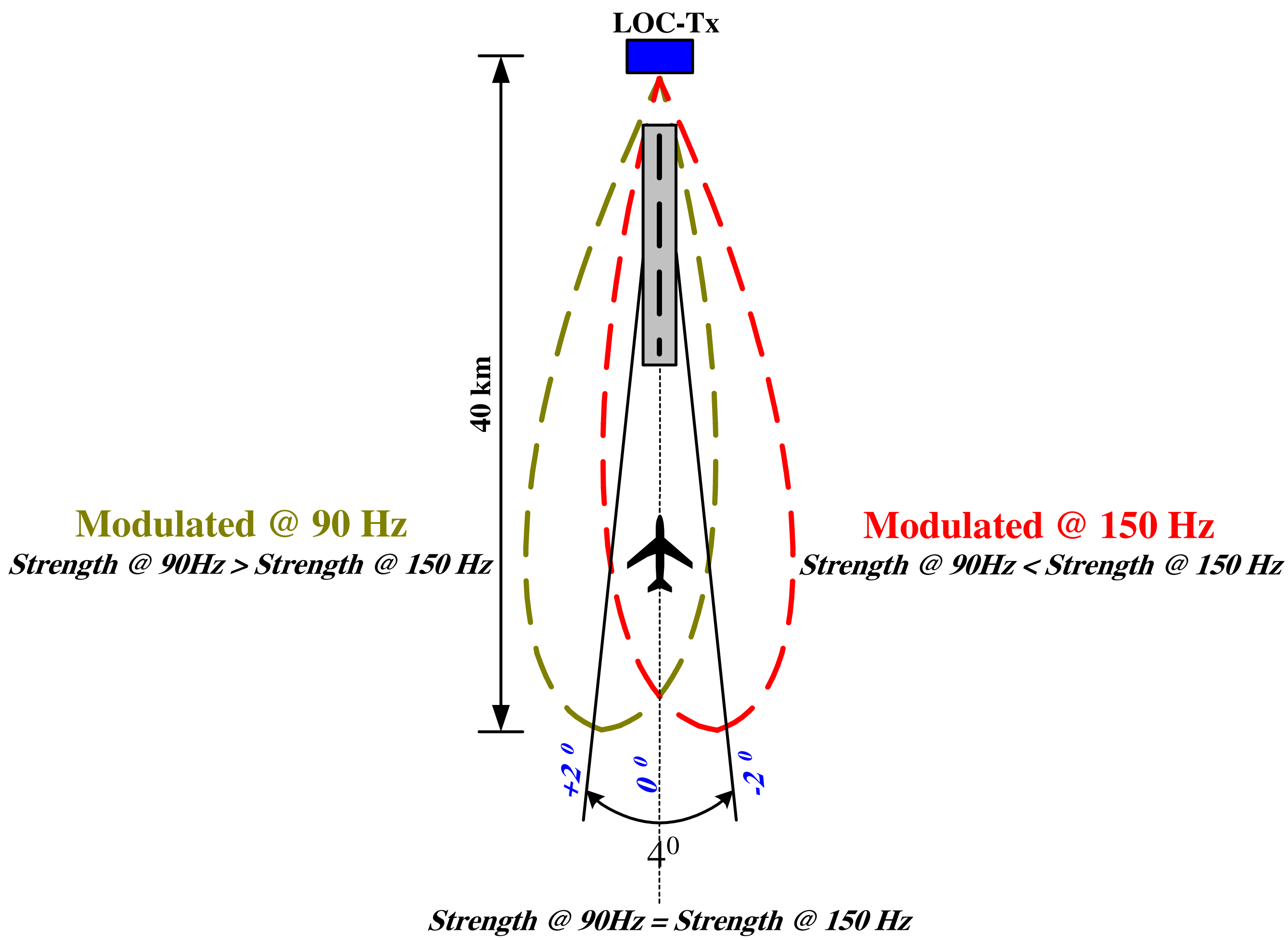


Figure-7.9 ILS-LOC ***[K6-31]***

2) *GS⁰–Tx*

- *Function: Provides fix descent rate.*
- *NAV: Vertical Guidance.*
- *Quantity per runway: 1*
- *Location: On the side of the runway.*
- *Frequency: UHF ≈ 329 – 335 MHz*
    - Number of Channels: *20*
- *Vertical Range of Operation ≈ 1 km*
- *Typical GS⁰ Inclination ≈ 3^0*
- *Deviation from GS⁰ ≈ $\pm 0.7^0$ [i.e. 1.4^0]*

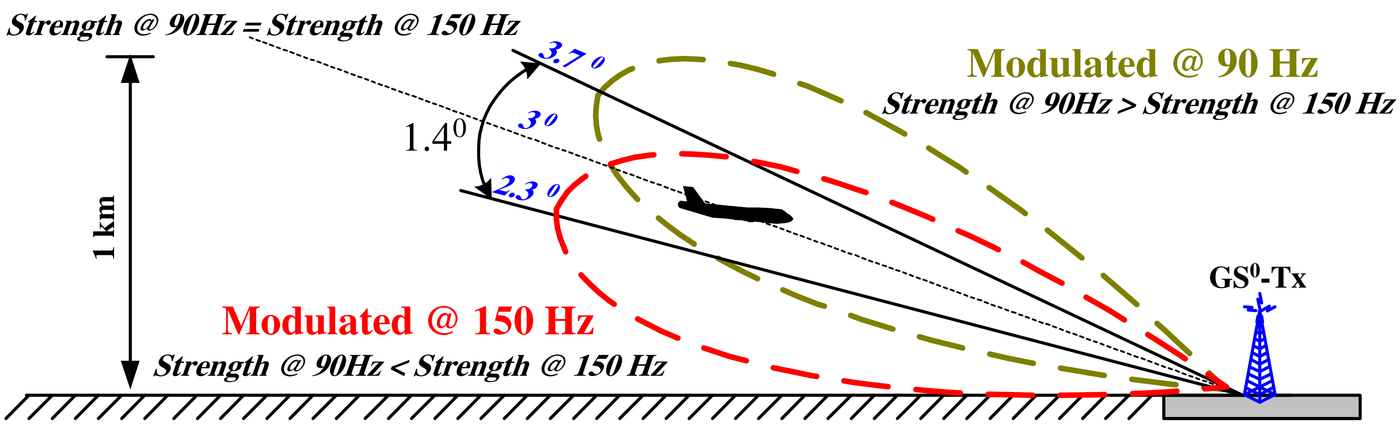


Figure-7.10 ILS-GS⁰ *[K6-31]*

3) *MB–Tx*[84]

- *Function: Provides indication to crew that the A/C is in a specific location.*
- *NAV: Horizontal Guidance.*
- *Quantity per runway: 2 or 3* [85]
- *Location: Prior to runway along its centerline.*
- *Frequency: VHF ≈ 75 MHz*

[84] NDB (Non-Directional Beacon) and MB (Marker Beacon) differ in the sense that NDB transmit signals in all directions, whereas MB emits in the upward direction only.

[85] All runway CATs have 3 MBs (OM, MM and IM) except CAT-I contains only 2 MBs (OM and MM).

LOC-Tx

GS⁰-Tx

MB-Tx

Figure-7.11 LOC, GS^0, and MB-Txs ***[K5-5]***

4) ***Transmissometer:*** *System used to measure the transmission of light through the atmosphere in order to determine visibility, and hence RVR.*

- *Function: System used to measure the transmission of light through the atmosphere in order to determine visibility, and hence RVR.*

- *Quantity per runway: 2*

- *Location: On the side of the runway.*

- *Range of Operation ≈ 10 km*

- *The system is able to identify 7 different types of pricipitation:*
  - Drizzle (i.e. gentle rain) || Rain
  - Frizzing Drizzle || Freezing Rain
  - Mixed Rain & Snow
  - Snow || Ice pellets

Figure-7.12 Transmissometer ***[K4-11]***

- **<u>In the A/C:</u>**

1) ***LOC/GS^0–Rx or HSI–System***[86]

❖ *Frequency:*
  ➢ VHF: *LOC*
  ➢ UHF: *GS^0*

❖ *Rx compares the strength of the 90 and 150 Hz modulated signals for both LOC and GS^0, and outputs the actual A/C position w.r.t. ideal centered path.*

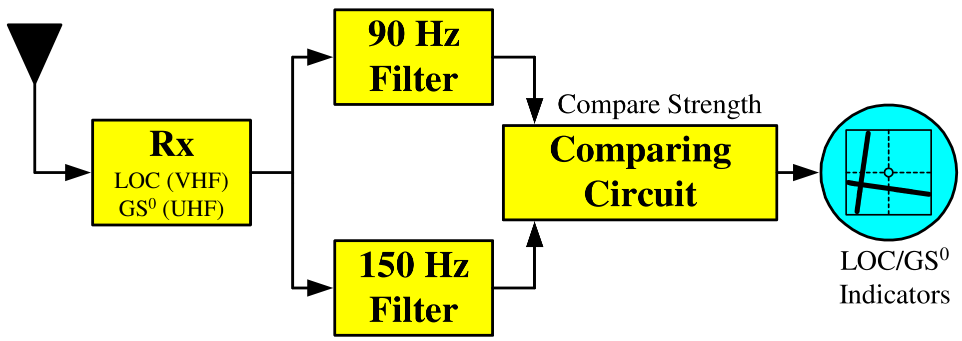
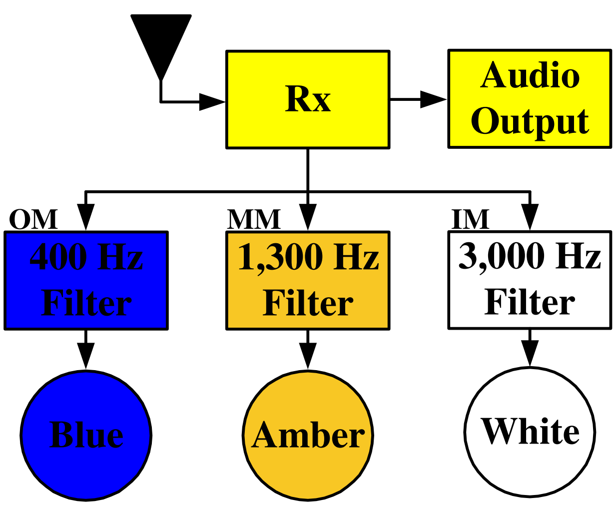


Figure-7.13 LOC/GS^0-Rx ***[K3-28]***

2) ***MB–Rx***

❖ *Frequency: VHF*

❖ *Rx detected the signal sent by the GND MB-Tx and alerts the A/C crew audibly and visually.*



MB	Audible Alerts		Visual Alerts
	Tone Freq	Morse Code	Color
OM	400 Hz	Continuous: ▬	Blue
MM	1,300 Hz	Alternate: ● & ▬	Amber
IM	3,000 Hz	Continuous: ●	White

Figure-7.14 MB-Rx and its alerts ***left:[K3-29] right:[K6-28]***

[86] For more on HSI refer to pages-68 & 69.

- **Advantage:** ILS is a powerful system available for landing guidance.

- **Disadvantages:**

  1) *LOC and GS⁰ signals suffer from bending due to site and terrain effect.*

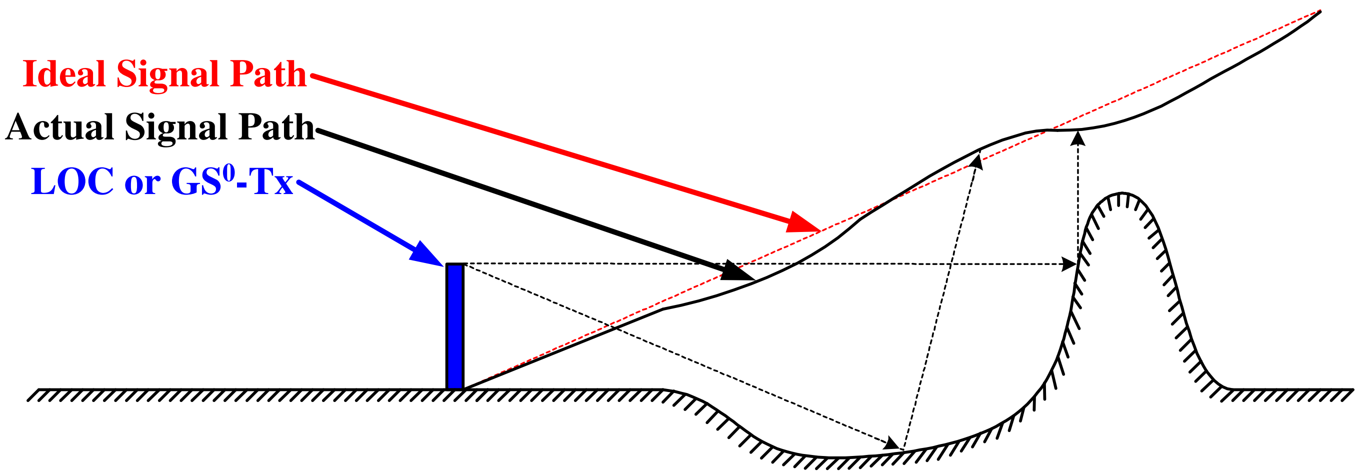


Figure-7.15 Terrain effect in ILS *[K3-30]*

  2) *GS⁰ signals are highly sensitive w.r.t. LOC; and therefore, they are also affected by:*

     - Snow
     - Airport GND moisture
     - Airport GND vehicle movement

  3) *The path used for landing in ILS cannot be flexible; it must remain straight at all times.*

  4) *Only 20 frequency channels are available for LOC and GS⁰ use.*

  5) *High cost of installation and maintenance.*

- **Future:** ILS is expected activity until *2010* in most A/Cs and airports; following that, it will remain available as a backup system in case an unexpected malfunction occurs to GPS and/or DGPS.

7.3 Microwave Landing System – MLS

- **Principle:** Provides A/C guidance for curved or straight or segmented flight path landing. The main outputs obtained using MLS are bearing, slant distance[87], and ALT in the approach terminal area. Also it is important to mention the MLS system is exclusively used by MIL[88] due to its flexibility in A/L as opposed to the CIV ILS.

[87] Usually a DME system (UHF) is integrated within the Azimuth-Tx (SHF), and hence the slant distance w.r.t. it is also available.
[88] Even tough MLS is a MIL system, some EU countries, due to visibility conditions, have obtained license for commercial use to operate them as an alternative for ILS.

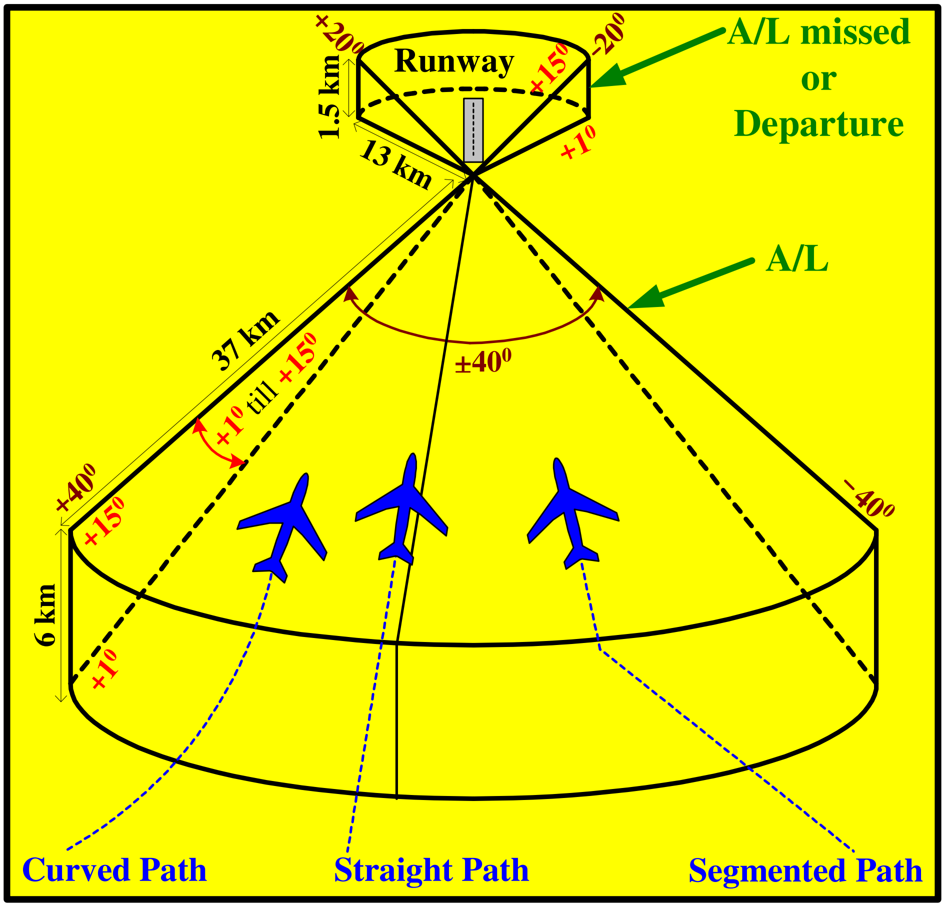


Figure-7.16 MLS *[K6-32]*

- **<u>On the GND:</u>**

  1) ***Azimuth–Tx***

     ❖ *Function: Provides bearing information.*

     ❖ *NAV: Horizontal Guidance.*

     ❖ *Quantity per runway: 2*

     ❖ *Location: One is placed at the end of the runway, and the other one at the begging* [89].

     ❖ *Frequency: SHF ≈ 5.031 – 5.0907 GHz*
        ➢ Number of Channels: *200*

     ❖ *Horizontal Range of Operation ≈ 37 km*

     ❖ *Deviation from Centerline ≈ ± 40^0 [i.e. 80^0]* [90]

---

[89] The one located at the end of the runway is used for approaching A/Cs, whereas the one located at the front of the runway is used for either missed approaches or for departure NAV.
[90] MLS horizontal guidance has a coverage area *20-times* that of ILS (*20* × *4^0* = *80^0*).

2) *Elevation–Tx*

- *Function: Provides ALT information.*
- *NAV: Vertical Guidance.*
- *Quantity per runway: 1*
- *Location: On the side of the runway.*
- *Frequency: SHF ≈ 5.031 – 5.0907 GHz* [91]
  - Number of Channels: *200*
- *Vertical Range of Operation ≈ 6 km*
- *Typical MLS Inclination ≈* 8^0
- *Deviation from MLS ≈* $\pm 7^0$ *[i.e.* 14^0*]* [92]

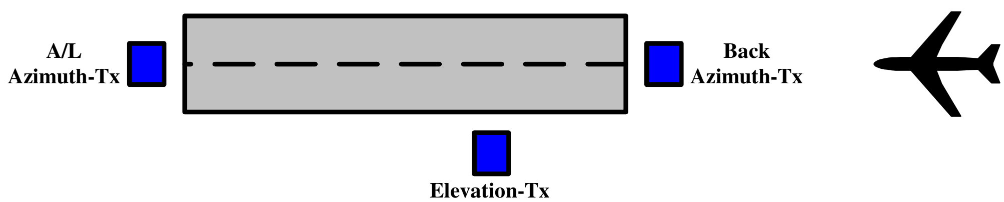


Figure-7.17 Configuration of MLS GND systems *[K6-33]*

Figure-7.18 Azimuth and Elevation-Txs *[K5-6]*

[91] Even though Azimuth and Elevation-Txs transmit at the same frequency, there is no critical signal interference among them due to timeshared operations.

[92] MLS vertical guidance has a coverage area *10-times* that of ILS ($10 \times 1.4^0 = 14^0$).

- **<u>In the A/C:</u>**

    1) *Rx: MLS-Rx system.*

    2) *Frequency: SHF*

    3) *Primary outputs from MLS:*
        - Bearing / Slant Distance
        - ALT

    4) *Secondary outputs from MLS:*
        - Meteorological info
        - Runway Status
        - Etc.

- **<u>Advantages:</u>**

    1) *Improved guidance accuracy with greater coverage area.*
    2) *Provide flexible landing path NAV.*
    3) *Offers guidance for missed approaches and departure NAV.*
    4) *MLS has low sensitivity from weather conditions and airport GNS traffic as oppose to ILS.*
    5) *MLS offers 200 frequency channels, 10-times more than ILS.*
    6) *Low cost of installation and maintenance.*

- **<u>Disadvantage:</u>** The use of MLS is not quite spread among CIV A/Cs.

- **<u>Future:</u>** Similar to ILS, MLS is expected to be phased-out around *2010* due to GPS and DGPS improved accuracy.

7.4 Differential Global Positioning System – DGPS

- **<u>Principle:</u>** GND system used to increase GPS accuracy. In fact, DGPS is typically found in airports in order to bring a more precise A/C position fix during the A/L phases. As for the A/C, it must be equipped with a GPS-Rx so that signals from both SAT and DGPS would be observed to correct position errors.

Figure-7.19 DGPS ***[K4-12]***

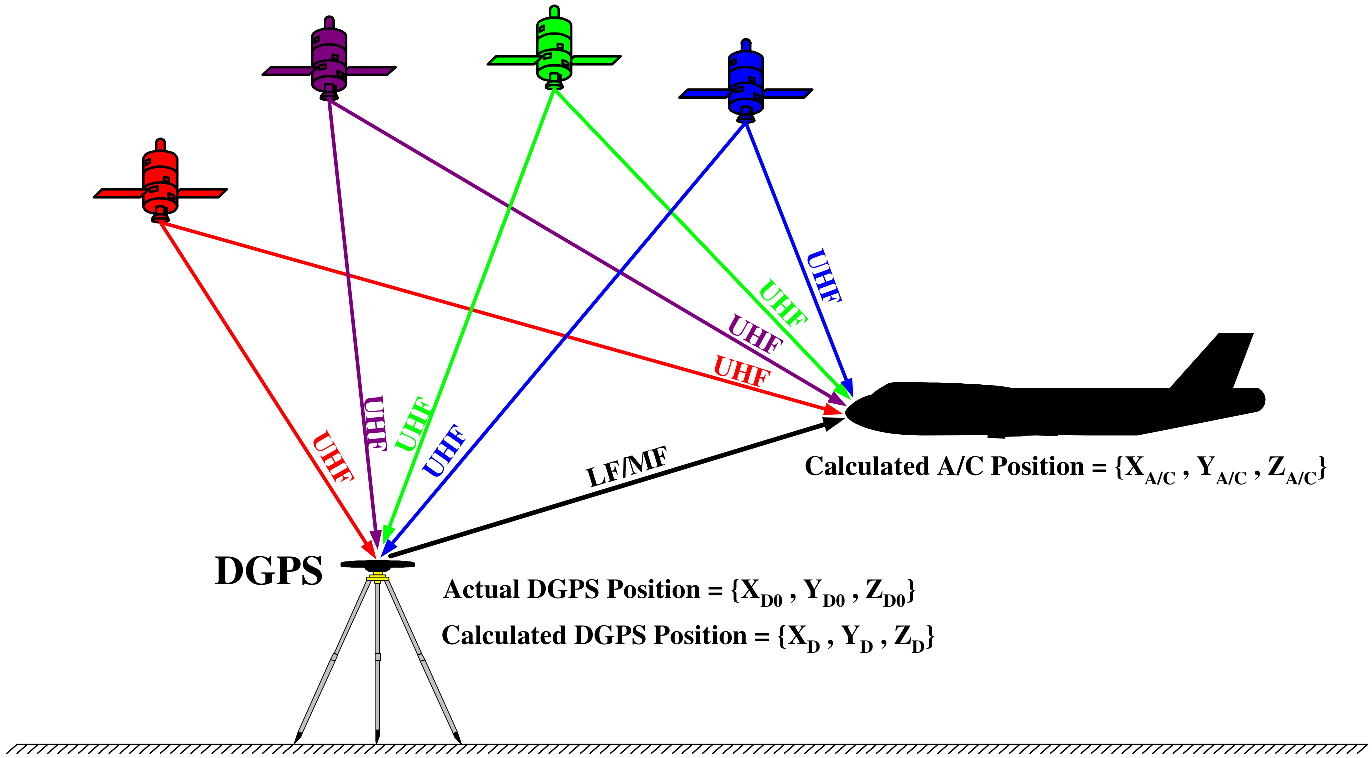


Figure-7.20 DGPS used to correct A/C position fix *[K6-34]*

- **<u>On the GND:</u>**

1) *Rx-Tx: DGPS system.*

2) *Frequency:*
   - *Rx: UHF [used to calculate DGPS position fix]*
   - *Tx: LF/MF ≈ 283.5 – 325 kHz [used to transmit correction signal to A/C]*

3) *The DGPS is stationary, therefore its actual {LAT_{D0}, LON_{D0}, ALT_{D0}}*[93] *is well known. Then we could use Equation-6.7 to transform it to {X_{D0}, Y_{D0}, Z_{D0}}.*

4) *Similar to what was seen in the GPS section of Chapter-6, we would use 4-SATs to obtain a 3D position fix for the DGPS. This calculated position is identified as {X_D, Y_D, Z_D}.*

5) *The DGPS then takes the difference that exists between the actual known position and the calculated position obtained using GPS SATs.*

$$\Delta = Calculated\ Position - Actual\ Position \tag{7.2}$$

$$\Delta = \overset{\substack{Calculated\ DGPS \\ Position}}{\begin{pmatrix} X_D \\ Y_D \\ Z_D \end{pmatrix}} - \overset{\substack{Actual\ DGPS \\ Position}}{\begin{pmatrix} X_{D0} \\ Y_{D0} \\ Z_{D0} \end{pmatrix}} \tag{7.3}$$

[93] Even if DGPS is located on the GND, it still has a height for its antenna and therefore, we consider a *3D = {LAT, LON, ALT}* position rather than a *2D = {LAT, LON}* position.

6) *Ideally, Δ should be roughly zero; however, most of the time this is not the case, and therefore the Δ information is transmitted to the airborne GPS-Rx in the form of a correction signal.*

- **In the A/C:**

1) *Rx: GPS-Rx system.*

2) *Frequency:*
   - *Rx: UHF [used to calculate A/C position fix]*
   - *Rx: LF/MF [used to observe correction signal from DGPS]*

3) *Range of Operation ≈ 370 km* [94]

4) *Again, the A/C obtains its 3D position fix using the 4-SATs.*

5) *Then, the GPS-Rx detects the correction signal that contains the Δ information and performs the following correction:*

$$Actual\ \ Position = Calculated\ \ Position - \Delta \tag{7.4}$$

$$Actual\ \ A/C\ \ Position = \overbrace{\begin{pmatrix} X_{A/C} \\ Y_{A/C} \\ Z_{A/C} \end{pmatrix}}^{\text{Calculated A/C Position}} - \Delta \tag{7.5}$$

- **Advantages:**

1) *GPS is quite accurate; however, using DGPS pushes its accuracy even further.*
2) *GPS/DGPS makes A/L guidance every precise as oppose to ILS and MLS.*

- **Disadvantages:**

1) *Errors:*

Accuracy	Errors [m]
Horizontal (i.e. LAT & LON)	1.3
Vertical (i.e. ALT)	2

Figure-7.21 Typical DGPS errors *[K3-31]*

[94] In other words, the maximum distance that separates the GND DGPS and the airborne GPS-Rx cannot exceed *370 km*.

2) *Most of the errors are either completely eliminated or made negligible after using DGPS; however, atmospheric (i.e. Ionosphere & Troposphere) and Rx-based (i.e. Rx-Noise & Multipath) errors would still exist.*

Error Sources	**DGPS Errors [m]**
SAT Clocks	0.0
Orbital Error	0.0
Ionosphere	0.4
Troposphere	0.2
Rx Noise	0.3
Multipath	0.6
Total	**1.5**

Figure-7.22 DGPS error sources *[K6-27]*

3) *The coverage area to take advantage of DGPS is limited.*

4) *To ensure greater coverage area more DGPS stations need to be added.*

5) *The position accuracy degrades as the separation between DGPS and A/C GPS-Rx increases.*

- **<u>Future:</u>**

1) *Currently there are 84-DGPS stations in the US*[95]*. 44 more DGPS sites are expected to be added in the next 15-years.*

2) *Likewise, in Canadian territories there exist 19-DGPS stations*[96]*. Addition of more stations is expected in the near future.*

3) *There are also systems that exist today and have promising future that are based on DGPS such as:*

❖ *Wide Area Augmentation System (WAAS):* It is based on 25-GND stations spread strategically ***across the US***. Similar to DGPS the difference between the actual position and the calculated position using GPS SATs is obtained for each of the stations. Then their data are sent to the WAAS Master Station (WMS) to be compiled; once this is done, a correction

[95] For present US DGPS status refer to: ***www.navcen.uscg.gov/ado/DgpsCompleteConfiguration_tabular.asp***
[96] For present Canadian DGPS status refer to: ***Atlantic Cost*** ***www.ccg-gcc.gc.ca/dgps/dgpsatlantic_e.htm***
Pacific Coast ***www.ccg-gcc.gc.ca/dgps/dgpspac_e.htm***
Great Lakes and St. Lawrence River ***www.ccg-gcc.gc.ca/dgps/dgpscen_e.htm***

signal is directed to WAAS SATs [97], which in turn transmit the signal to GPS-Rxs for position correction.

- *Local Area Augmentation System (LAAS):* This system is very similar to WAAS but on a much smaller scale[98]. Again here, GND stations are located at known positions ***across the airport***, then a calculated position fix is obtained for each of these stations and the offset is measured. Once this is done, offsets from each station are sent to the airport central location for compilation purposes. Finally, the correction signal is sent from the central location to airborne GPS-Rxs.

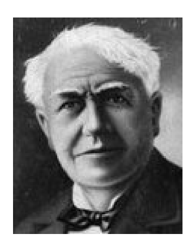
[97] WAAS SATs are not GPS SATs; they are specifically used to transmit the correction signal to GPS-Rxs.
[98] WAAS is based on a large network across the US; whereas LAAS is a network used within an airport. That is, each airport contains its own LAAS system for guidance in the precision A/L phase. It is also interesting to note that both of these systems are developed and maintained by the FAA.

Chapter 8

Summary

There is no substitute for
hard work.

— Thomas Edison



8.1 Nomenclature

2D	Latitude and Longitude
3D	Latitude, Longitude, and Altitude
A/C	Aircraft
AFIS	Airborne Flight Information System
A/L	Approach Landing
ATC	Air Traffic Control
ELT	Emergency Locator Transmitter
GND	Ground
HF	High Frequency
IFR	Instrument Flight Rule
LF	Low Frequency
MF	Medium Frequency
MIL	Military System
NAV	Navigation
NAVAIDS	Navigational Aids

OS	Outer-Space
P/O	Phased-Out systems
RA	Radio Altimeter
Rx	Receiver
SATCOM	Satellite Communications
SHF	Super High Frequency
TCAS	Traffic-Alert and Collision Avoidance System
Tx	Transmitter
UHF	Ultra High Frequency
VFR	Visual Flight Rule
VHF	Very High Frequency
VLF	Very Low Frequency
WPT	Waypoint
W.R.T.	With Respect To
WXR	Weather Radar System

8.2 Summary of Avionic Systems

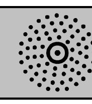
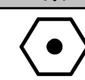
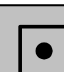
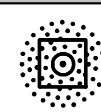
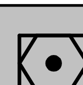
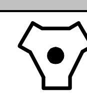
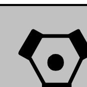
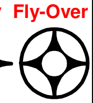
RANGE	SYSTEM	MEANING	PRINCIPLE	FREQUENCY	SYSTEM LOCATION			CHART SYMBOL	MIL	P/O
					GND	A/C	OS			
Short-Range NAVAIDS Continental NAV	**ADF**	**A**utomatic **D**irection **F**inder	Provides A/C bearing w.r.t. a GND station	**MF**		✓				✓
	NDB	**N**on-**D**irectional **B**eacon	GND system used as an ADF Tx for bearing purposes	**MF**	✓					✓
	VOR	**V**HF **O**mni-directional **R**ange	Provides A/C radial w.r.t. a GND station	**VHF**	✓	✓				
	DME	**D**istance **M**easuring **E**quipment	Provides distance between A/C and GND station	**UHF**	✓	✓				
	NDB-DME	**NDB** & **DME**	GND system with both NDB and DME for bearing and distance purposes	**MF / UHF**	✓					
	VOR-DME	**VOR** & **DME**	GND system with both VOR and DME for radial and distance purposes	**VHF / UHF**	✓					
	TACAN	**TAC**tical **A**ir **N**avigation	Provides A/C bearing and distance w.r.t. a GND station	**UHF**	✓	✓			✓	
	VORTAC	**VOR** & **TAC**AN	GND system with both VOR and TACAN for bearing and distance purposes	**VHF / UHF**	✓				✓	
	RNAV	**R**andom **NAV**igation or a**R**ea **NAV**igation	Provides A/C bearing and distance w.r.t. 3D artificial reference position known as WPT	**VHF / UHF** **SHF**		✓		Fly-By  Fly-Over 		

Figure-8.1 Short-Range Avionics

RANGE	SYSTEM	MEANING	PRINCIPLE	FREQUENCY	SYSTEM LOCATION			CHART SYMBOL	MIL	P/O
					GND	A/C	OS			
Long-Range NAVAIDS Intercontinental NAV	LORAN-C	LOng RAnge Navigation (revision-C)	Provides A/C position fix (2D)	LF	✓	✓				✓
	OMEGA	Optimized Method for Estimated Guidance Accuracy	Provides A/C position fix (2D)	VLF	✓	✓				✓
	INS or IRS	Inertial Navigation or Reference System	Provides A/C velocity (3D) and position fix (3D)	------		✓				
	DNS	Doppler Navigation System	Provides A/C velocity (3D) and position fix (3D)	SHF		✓			✓	
	GPS	Global Positioning System	Provides A/C position fix (3D)	UHF	✓	✓	✓			

Figure-8.2 Long-Range Avionics

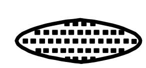
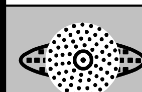
RANGE	SYSTEM	MEANING	PRINCIPLE	FREQUENCY	SYSTEM LOCATION			CHART SYMBOL	MIL	P/O
					GND	A/C	OS			
Approach-Landing NAVAIDS Terminal-Area NAV	ALS	Approach Lighting System	Provides visual aid during landing for IFR-precision A/C	------	✓					
	VASIS	Visual Approach Slope Indicator System	Provides visual aid during landing for VFR and IFR-non-precision A/C	------	✓					
	ILS	Instrument Landing System	Provides A/C guidance for straight flight path landing	VHF / UHF	✓	✓				
	LOC	LOCalizer	Provides horizontal guidance during ILS landing	VHF	✓	✓				
	GS^0	GlideSlope	Provides vertical guidance during ILS landing	UHF	✓	✓				
	LOC-DME	LOC & DME	GND system with both LOC and DME for horizontal guidance during ILS landing and distance purposes	VHF / UHF	✓					
	MB	Marker Beacon	Provides indication that the A/C is in a specific location	VHF	✓	✓				
	OM MM IM	Outer Marker Middle Marker Inner Marker	Provides indication on how far the A/C is w.r.t. the runway threshold	VHF	✓	✓				
	MLS	Microwave Landing System	Provides A/C guidance for curved or straight or segmented flight path landing	SHF	✓	✓			✓	
	DGPS	Differential GPS	GND system used to increase GPS accuracy	LF / MF UHF	✓					

Figure-8.3 A/L Avionics

8.3 Avionic Receivers and/or Transmitters

RANGE	SYSTEM	On the GND		In the A/C		In Space	
		Tx	Rx	Tx	Rx	Tx	Rx
Short-Range Continental	ADF	---	---	---	✓	---	---
	NDB	✓	---	---	---	---	---
	VOR	✓	---	---	✓	---	---
	DME	✓	✓	✓	✓	---	---
	TACAN	✓	✓	✓	✓	---	---
	VORTAC	✓	✓	---	---	---	---
Long-Range Intercontinental	LORAN-C	✓	---	---	✓	---	---
	OMEGA	✓	---	---	✓	---	---
	DNS	---	---	✓	✓	---	---
	GPS	✓	✓	---	✓	✓	✓
A/L Phase Terminal-Area	ILS	✓	---	---	✓	---	---
	MB	✓	---	---	✓	---	---
	MLS	✓	---	---	✓	---	---
	DGPS	✓	✓	---	---	---	---

Figure-8.4 Avionic Rxs and/or Txs

8.4 Airborne Antennas

Short-Range NAVAIDS
Long-Range NAVAIDS
A/L NAVAIDS
Short-Range & A/L NAVAIDS
Other

Figure-8.5 Color coding used to classify avionics

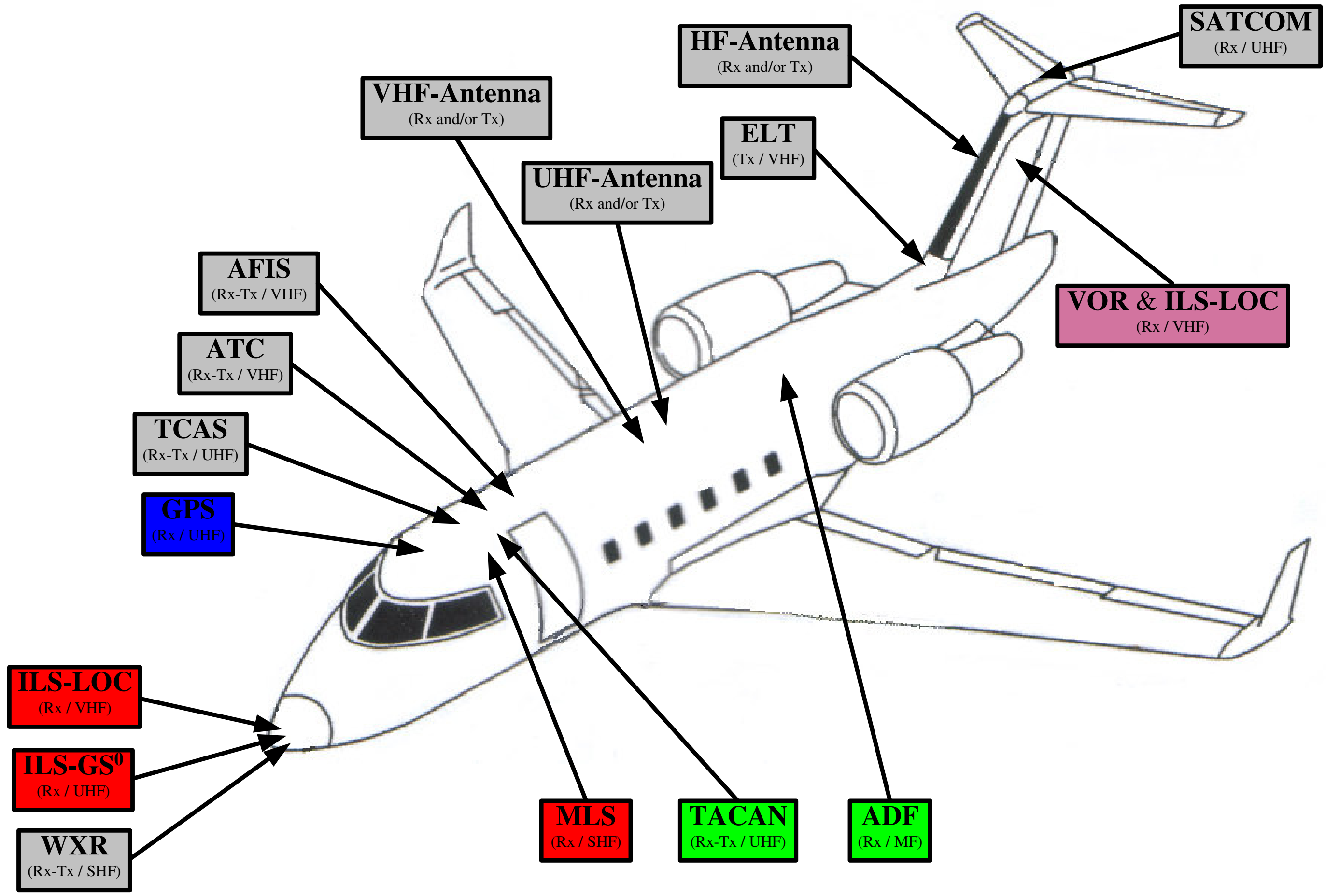


Figure-8.6 Top-view of airborne avionics ***[K2-2]***

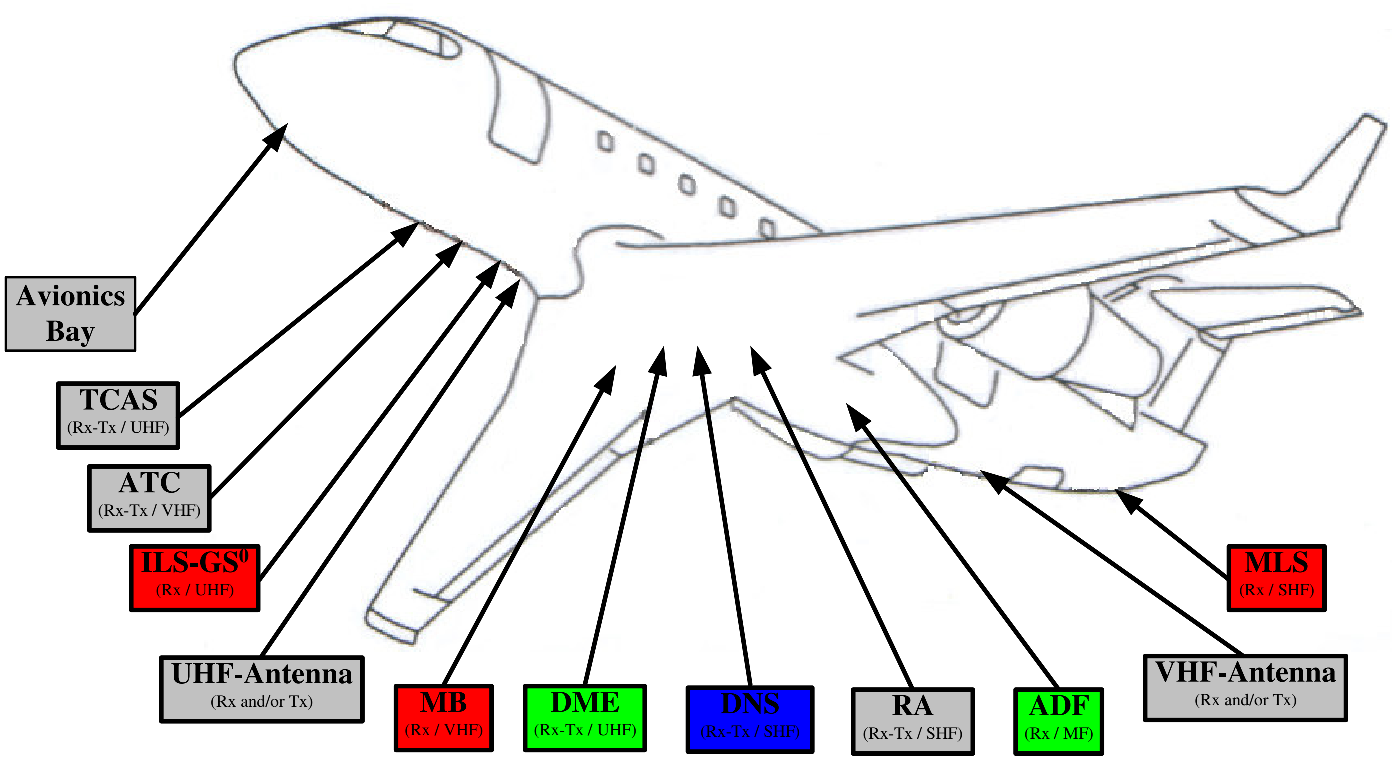


Figure-8.7 Bottom-view of airborne avionics ***[K2-2]***

Appendices

Appendix A: Matlab code that transforms LAT or LON from hour/minute/second to decimal format

```
%HMS_TO_DECIMAL  Transforms latitude or longitude from
%                hour/minute/second format to a decimal degree format
%
%DEC = HMS_TO_DECIMAL(HH,MM,SS,'DIRECTION')
%
%'DIRECTION' could take 4 type of inputs (case sensitive/ must be in CAPS):
%         'N' - for North -> Latitude will be +
%         'S' - for South -> Latitude will be -
%         'E' - for East  -> Longitude will be +
%         'W' - for West  -> Longitude will be -
%
%HH - refers to hours or degrees -> If 'N' or 'S' is used HH possible set = {0 , 90}
%                                -> If 'E' or 'W' is used HH possible set = {0 , 180}
%
%MM - refers to minutes -> MM possible set = {0 , 60}
%
%SS - refers to seconds -> SS possible set = (0 , 60}
%
%DEC - refers to degrees in decimal format
%
%Example: Montréal/QC/Canada LAT: 45deg 30min 0sec North || LON: 73deg 35min 0sec West
%         LAT_DEC = HMS_TO_DECIMAL(45,30,0,'N') -> LAT_DEC =   45.5000
%         LON_DEC = HMS_TO_DECIMAL(73,35,0,'W') -> LON_DEC = - 73.5833
%
%See also DECIMAL_TO_HMS.
%Mouhamed Abdulla, October 2005

function dec = hms_to_decimal(hh,mm,ss,di)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%Validating Inputs%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
if((di~='N') & (di~='S') & (di~='E') & (di~='W'))
 error('Invalid "direction" entered! Valid values are N or S or E or W, and they must be in CAPS!')
end

if((di=='N') | (di=='S'))
 if((hh<0) | (hh>90))
  error('Invalid "hours" or "degrees" entered! Value must be within "0" to "90" inclusive.')
 end
end

if((di=='E') | (di=='W'))
 if((hh<0) | (hh>180))
  error('Invalid "hours" or "degrees" entered! Value must be within "0" to "90" inclusive.')
 end
end

if((mm<0) | (mm>60))
 error('Invalid "minutes" entered! Value must be within "0" to "60" inclusive.')
end

if((ss<0) | (ss>60))
 error('Invalid "seconds" entered! Value must be within "0" to "60" inclusive.')
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%Transformation%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
if((di=='N') | (di=='E'))
  sign = 1;
else
  sign = -1;
end
temp = (((ss/60) + mm) / 60) + hh;
dec = sign * temp;
```

Appendix B: Matlab code that transforms LAT or LON from decimal to hour/minute/second format

```
%DECIMAL_TO_HMS  Transforms latitude or longitude from decimal degree format
%                to hour/minute/second format
%
%[HH,MM,SS,'DIRECTION'] = DECIMAL_TO_HMS(DEC,'X')
%
%'X' could take 2 type of inputs (case sensitive/ must be in CAPS): 'LAT' - for Latitude
%                                                                   'LON' - for Longitude
%
%DEC - refers to degrees in decimal format -> If 'LAT' is used DEC possible set = {-90 , 90}
%                                          -> If 'LON' is used DEC possible set = {-180 , 180}
%
%HH - refers to hours or degrees
%
%MM - refers to minutes
%
%SS - refers to seconds
%
%'DIRECTION' could refer to either: 'N' - for North
%                                   'S' - for South
%                                   'E' - for East
%                                   'W' - for West
%
%Example: Montréal/QC/Canada LAT: 45.5000 || LON: -73.5833
%         [H1,M1,S1,D1] = DECIMAL_TO_HMS( 45.5000,'LAT') -> H1 = 45 | M1 = 30 | S1 =  0     | D1 = N
%         [H2,M2,S2,D2] = DECIMAL_TO_HMS(-73.5833,'LON') -> H2 = 73 | M2 = 34 | S2 = 59.8800| D2 = W
%
%
%See also HMS_TO_DECIMAL.
%Mouhamed Abdulla, October 2005

function [hh,mm,ss,di] = decimal_to_hms(dec,x)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%Validating Inputs%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
if(~strcmp(x,'LAT') & ~strcmp(x,'LON'))
   error('Invalid "X" entered! Valid values are LAT or LON, and they must be in CAPS!')
   return
end

if(x=='LAT')
 if((dec<-90) | (dec>90))
  error('Invalid "degrees" entered! Value of LAT must be within "-90" to "90" inclusive.')
 end
end

if(x=='LON')
 if((dec<-180) | (dec>180))
  error('Invalid "degrees" entered! Value of LON must be within "-180" to "180" inclusive.')
 end
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%Transformation%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
s = sign(dec);

if(x=='LAT')
 if(s==0 | s==1)
  di = 'N';
 else
  di = 'S';
 end
end

if(x=='LON')
 if(s==0 | s==1)
  di = 'E';
 else
  di = 'W';
 end
end
```

```
%FIX is a Matlab function that ignores any decimal and keeps the integer part only.
d = abs(dec);
hh = fix(d);
t1 = (d - hh) * 60;
mm = fix(t1);
t2 = t1 - mm;
ss = (t2 *60); %We could round the result here to get an integer "seconds" value,
               %or we could leave the way it is for the sake of greater accuracy.
```

Appendix C: ALT, Temperature, Pressure w.r.t. the Atmosphere

↑ *ALT* & ↑ *Temp* & ↓ *Air Molecules*

In this region temperature increases with an increase in altitude; however, our human skin will still freeze since air molecules are less, and hence less energy is transferred to our skin.

↑ *ALT* & ↓ *Temp* & ↓ *Air Molecules*

↑ *ALT* & ↑ *Temp* & ↓ *Air Molecules*

↑ *ALT* & ↓ *Temp* & ↓ *Air Molecules*

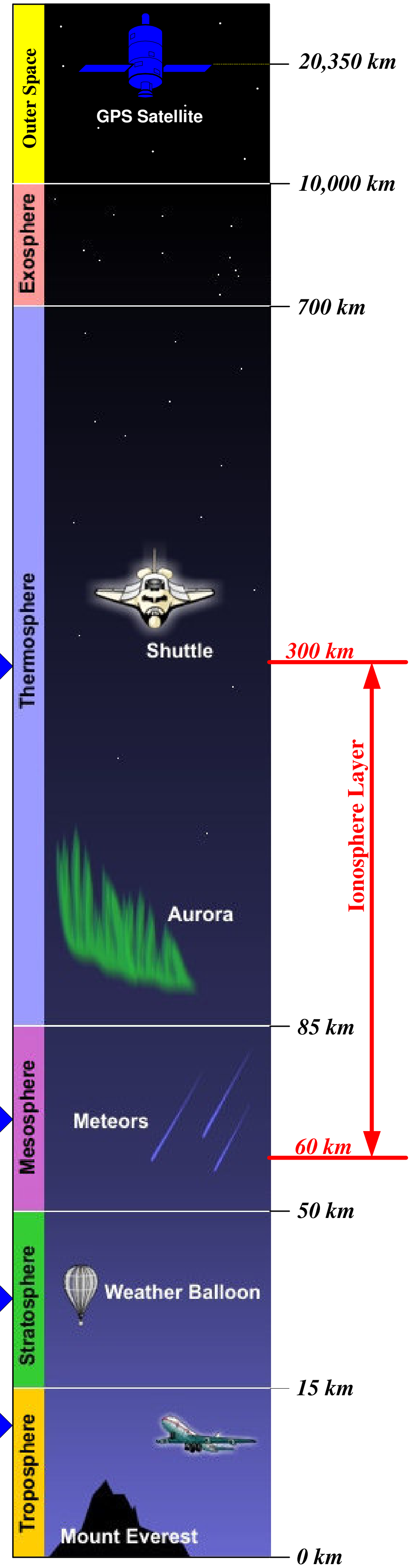


Figure-C.1 Atmosphere layers *[K5-7]*

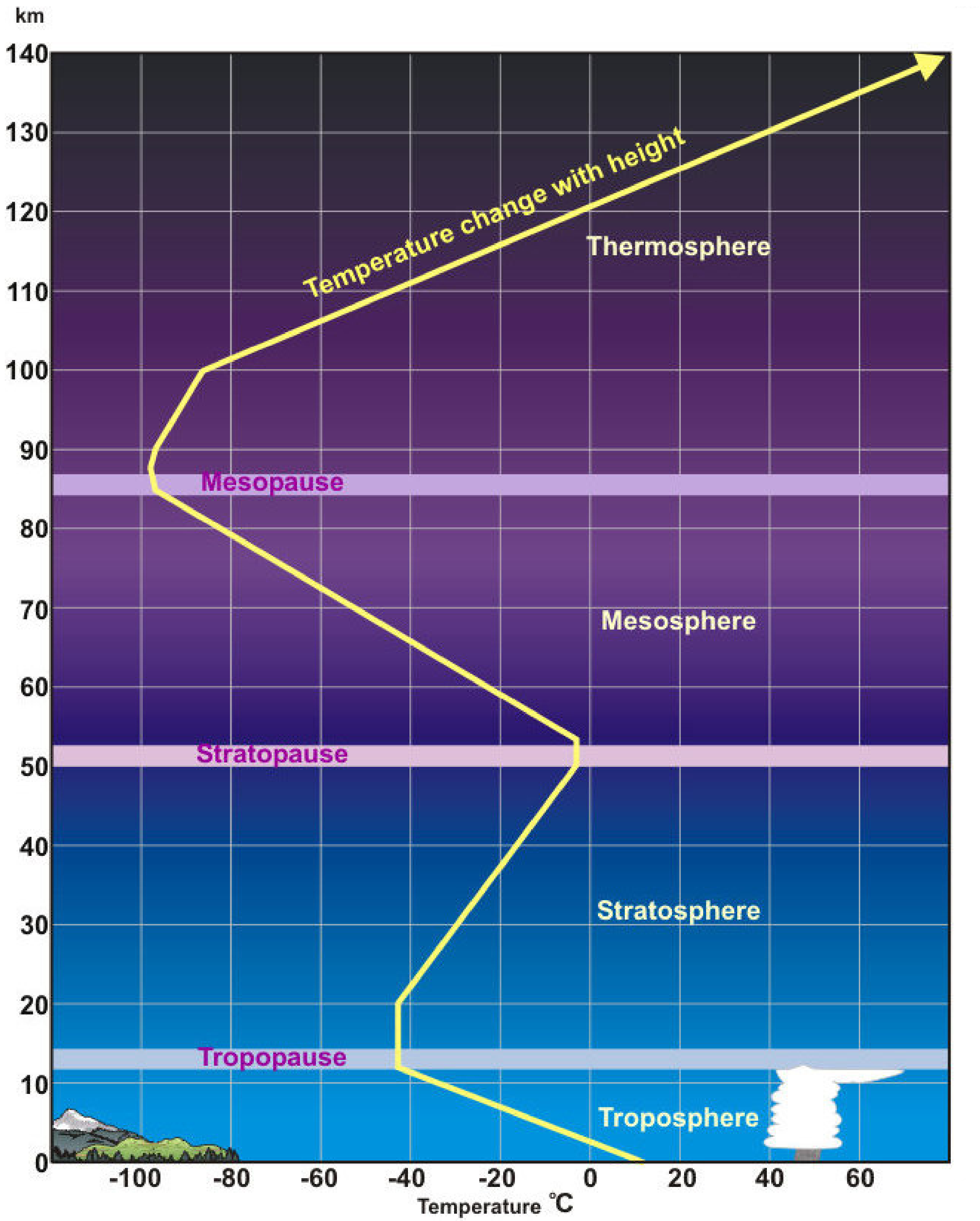
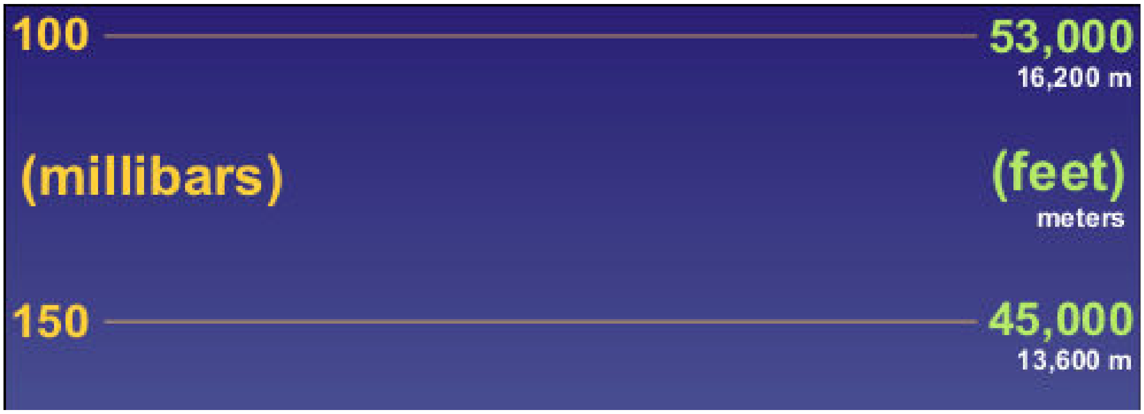


Figure-C.2 ALT as a function of temperature *[K5-8]*



Maximum ALT for a B747-400 = 40,000 ft = 12.2 km

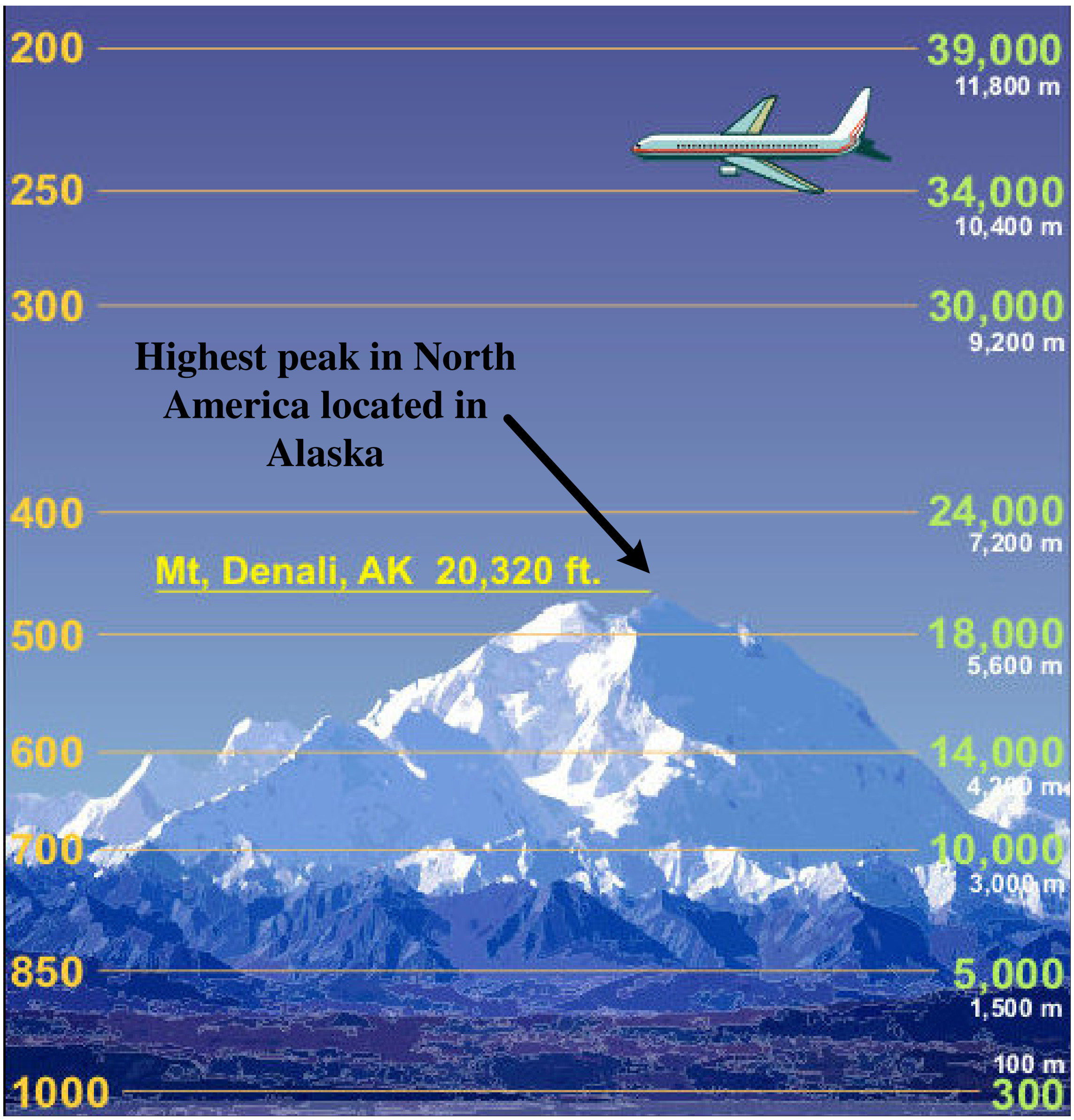


Figure-C.3 ALT as a function of pressure ***[K5-9]***

Appendix D: Matlab code that transforms *{X,Y,Z}* to *{LAT,LON,ALT}*

```
%XYZ_TO_LLA  Transforms Earth Centered Earth Fixed (ECEF) Cartesian system (X,Y,Z)
%            to geodetic system (LAT,LON,ALT)
%
%[LAT,LON,ALT] = XYZ_TO_LLA(X,Y,Z)
%
%X Y Z - refers to the ECEF coordinates in "meters"
%
%LAT - refers to latitude in "degrees".
%
%LON - refers to longitude in "degrees".
%
%ALT - refers to altitude in "meters".
%
%Example: X: 1109900 [m] || Y: -4860100 [m] || Z: 3965200 [m]
%         [LAT,LON,ALT] = XYZ_TO_LLA(1109900,-4860100,3965200) -> LAT = 38.6860 | LON = -77.1360 | ALT = 46.4497
%
%See also LLA_TO_XYZ.
%Mouhamed Abdulla, October 2005

function [lat,lon,alt] = xyz_to_lla(x,y,z)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%Transformation%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
a = 6378137;        %Earth equatorial radius
b = 6356752.3142;   %Earth polar radius
f = (a-b)/a;        %Flattening of ellipsoid
e2 = f*(2-f);             %First eccentricity of ellipsoid squared
ep2 = (a^2 - b^2) / b^2; %Second eccentricity of ellipsoid squared
p = sqrt(x^2 + y^2);
th = atan((z*a)/(p*b));

t1 = z + ep2 * b * (sin(th))^3;
t2 = p - e2 * a * (cos(th))^3;

latr = atan(t1/t2); %LAT in radians
lonr = atan2(y,x);  %LON in radians

lat = (180/pi)*latr; %LAT in degrees
lon = (180/pi)*lonr; %LON in degrees

v = a / sqrt(1 - (e2*(sin(latr))^2)); %Radius of curvature

alt = (p/cos(latr)) - v; %ALT in meters
```

Appendix E: Matlab code that transforms *{LAT,LON,ALT}* to *{X,Y,Z}*

```
%LLA_TO_XYZ  Transforms geodetic system (LAT,LON,ALT) to
%            Earth Centered Earth Fixed (ECEF) Cartesian system (X,Y,Z).
%
%[X,Y,Z] = LLA_TO_XYZ(LAT,LON,ALT)
%
%LAT - refers to latitude in "degrees" with possible set = {-90 , 90}
%
%LON - refers to longitude in "degrees" with possible set = {-180 , 180}
%
%ALT - refers to altitude in "meters" with possible set = {0, ALT>0}
%
%X Y Z - refers to the ECEF coordinates in "meters"
%
%Example: LAT: 38.6858 [deg] || LON: -77.1357 [deg] || ALT: 25 [m]
%         [X,Y,Z] = LLA_TO_XYZ(38.6858,-77.1357,25) -> X = 1.1099e+006 | Y = -4.8601e+006 | Z = 3.9652e+006
%
%See also XYZ_TO_LLA.
%Mouhamed Abdulla, October 2005

function [x,y,z] = lla_to_xyz(lat,lon,alt)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%Validating Inputs%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
if((lat<-90) | (lat>90))
 error('Invalid "degrees" entered! Value of LAT must be within "-90" to "90" inclusive.')
end

if((lon<-180) | (lon>180))
 error('Invalid "degrees" entered! Value of LON must be within "-180" to "180" inclusive.')
end

if(alt<0)
 error('Invalid "height" entered! Value of ALT must be "0" or above.')
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%Transformation%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
latr = (pi/180)*lat; %LAT in radians
lonr = (pi/180)*lon; %LON in radians

a = 6378137;        %Earth equatorial radius
b = 6356752.3142;   %Earth polar radius
f = (a-b)/a;        %Flattening of ellipsoid
e2 = f*(2-f);       %First eccentricity of ellipsoid squared
v = a / sqrt(1 - (e2*(sin(latr))^2)); %Radius of curvature

x = (v+alt) * cos(latr) * cos(lonr); %In meters
y = (v+alt) * cos(latr) * sin(lonr); %In meters
z = (v*(1-e2) + alt) * sin(latr);    %In meters
```

Appendix F: GPS SATs launched from *February-1978* until *November–2005*

SVN: Satellite Vehicle Number

GPS		SVN	Launch Date	Activation Date	Termination Date	Plane/Slot	Clock
GPS - I	Block I	01	1978 - 02 - 22	1978 - 03 - 29	1985 - 07 - 17	----	----
		02	1978 - 05 - 13	1978 - 07 - 14	1988 - 02 - 12	----	----
		03	1978 - 10 - 06	1978 - 11 - 13	1992 - 05 - 18	----	----
		04	1978 - 12 - 10	1979 - 01 - 08	1989 - 10 - 14	----	----
		05	1980 - 02 - 09	1980 - 02 - 27	1984 - 05 - 11	----	----
		06	1980 - 04 - 26	1980 - 04 - 16	1991 - 03 - 06	----	----
		07	1981 - 12 - 18	Unsuccessful Launch			
		08	1983 - 07 - 14	1983 - 08 - 10	1993 - 05 - 04	----	----
		09	1984 - 06 - 13	1984 - 07 - 19	1994 - 02 - 28	----	----
		10	1984 - 09 - 08	1984 - 10 - 03	1995 - 11 - 18	----	----
		11	1985 - 10 - 09	1985 - 10 - 30	1994 - 02 - 27	----	----
GPS - II	Block II	14	1989 - 02 - 14	1989 - 04 - 15	2000 - 04 - 14	----	----
		13	1989 - 06 - 10	1989 - 08 - 10	2004 - 05 - 12	----	----
		16	1989 - 08 - 18	1989 - 10 - 14	2000 - 10 - 13	----	----
		19	1989 - 10 - 21	1989 - 11 - 23	2001 - 09 - 11	----	----
		17	1989 - 12 - 11	1990 - 01 - 06	2005 - 02 - 23	----	----
		18	1990 - 01 - 24	1990 - 02 - 14	2000 - 08 - 18	----	----
		20	1990 - 03 - 26	1990 - 04 - 18	1996 - 12 - 13	----	----
		21	1990 - 08 - 02	1990 - 08 - 22	2003 - 01 - 27	----	----
		15	1990 - 10 - 01	1990 - 10 - 15	----	D5	Cs
	Block IIA	23	1990 - 11 - 26	1990 - 12 - 10	2004 - 02 - 13	----	----
		24	1991 - 07 - 04	1991 - 08 - 30	----	D1	Cs
		25	1992 - 02 - 23	1992 - 03 - 24	----	A2	Cs
		28	1992 - 04 - 10	1992 - 04 - 25	1997 - 08 - 15	----	----
		26	1992 - 07 - 07	1992 - 07 - 23	----	F2	Rb
		27	1992 - 09 - 09	1992 - 09 - 30	----	A4	Cs
		32	1992 - 11 - 22	1992 - 12 - 11	----	F6	Cs
		29	1992 - 12 - 18	1993 - 01 - 05	----	F5	Rb
		22	1993 - 02 - 03	1993 - 04 - 04	2003 - 08 - 06	----	----
		31	1993 - 03 - 30	1993 - 04 - 13	2005 - 10 - 24	----	----
		37	1993 - 05 - 13	1993 - 06 - 12	----	C4	Rb
		39	1993 - 06 - 26	1993 - 07 - 21	----	A1	Cs
		35	1993 - 08 - 30	1993 - 09 - 28	----	B4	Rb
		34	1993 - 10 - 26	1993 - 11 - 22	----	D4	Rb
		36	1994 - 03 - 10	1994 - 03 - 28	----	C1	Rb
		33	1996 - 03 - 28	1996 - 04 - 09	----	C2	Cs
		40	1996 - 07 - 16	1996 - 08 - 15	----	E3	Cs
		30	1996 - 09 - 12	1996 - 10 - 01	----	B2	Rb
		38	1997 - 11 - 06	1997 - 12 - 18	----	A3	Cs

(continued on the next page)

Figure-F.1 GPS Blocks-I, II and IIA *[K6-26]*

GPS		SVN	Launch Date	Activation Date	Termination Date	Plane/Slot	Clock
GPS - II	Block IIR	42	1997 - 01 - 17	Unsuccessful Launch			
		43	1997 - 07 - 23	1998 - 01 - 31	----	F3	Rb
		46	1999 - 10 - 07	2000 - 01 - 03	----	D2	Rb
		51	2000 - 05 - 11	2000 - 06 - 01	----	E1	Rb
		44	2000 - 07 - 16	2000 - 08 - 17	----	B3	Rb
		41	2000 - 11 - 10	2000 - 12 - 10	----	F1	Rb
		54	2001 - 01 - 30	2001 - 02 - 15	----	E4	Rb
		56	2003 - 01 - 29	2003 - 02 - 19	----	B1	Rb
		45	2003 - 03 - 31	2003 - 04 - 12	----	D3	Rb
		47	2003 - 12 - 21	2004 - 01 - 12	----	E2	Rb
		59	2004 - 03 - 20	2004 - 04 - 05	----	C3	Rb
		60	2004 - 06 - 23	2004 - 07 - 09	----	F4	Rb
		61	2004 - 11 - 06	2004 - 11 - 22	----	D7	Rb
	Block IIR-M	53	2005 - 09 - 26	----	----	D6	Rb

Figure-F.2 GPS Blocks-IIR and IIR-M ***[K6-26]***

Appendix G: Effect of Portable Electronic Devices (PEDs) on airborne avionics

While reading the statistics below keep in mind that:

- *Data was obtained from NASA's Aviation Safety Reporting System (ASRS)*[99].
- *Data was compiled and made presentable by [C23].*
- *Because of budget cuts only 10% of incidences are randomly processed.*
- *Incidences captured are not necessarily caused by the corresponding PED.*
- *However, in many of these cases, PEDs are considered the primary source of interference as observed from an OFF/ON test of PEDs.*
- *Obviously cell phones and laptop computers are more used by passengers and hence the interference caused by them is larger than any other PEDs.*

PEDs: Source of Interference	% of Incidents
Cell Phones	27.0
Laptop Computers	22.4
Unknown (most probably cell phones)	15.1
Electronic Games	9.8
AM/FM Radios	7.9
CD Players	4.6
Pagers	3.9
Video Cameras	2.0
Portable TVs	2.0
Transmitters	2.0
PDAs	0.7
Calculators	0.7
Heart Monitors	0.7
Hearing Aids	0.7
Other Electronic Devices	0.5

Avionics: Affected by Interference	% of Incidents
VOR	31.5
Other NAVAIDS	22.1
ILS	11.4
Communication Radio	8.1
RA	6.7
Autopilot	5.4
GPWS	4.7
TCAS	2.7
Compass	2.7
FD	2.0
Caution/Advisory Light	1.3
Gyro	0.7
Engine Fuel Controller	0.7

Figure-G.1 Percentage of PEDs interfering with avionic systems

[99] ASRS Website: ***http://asrs.arc.nasa.gov***

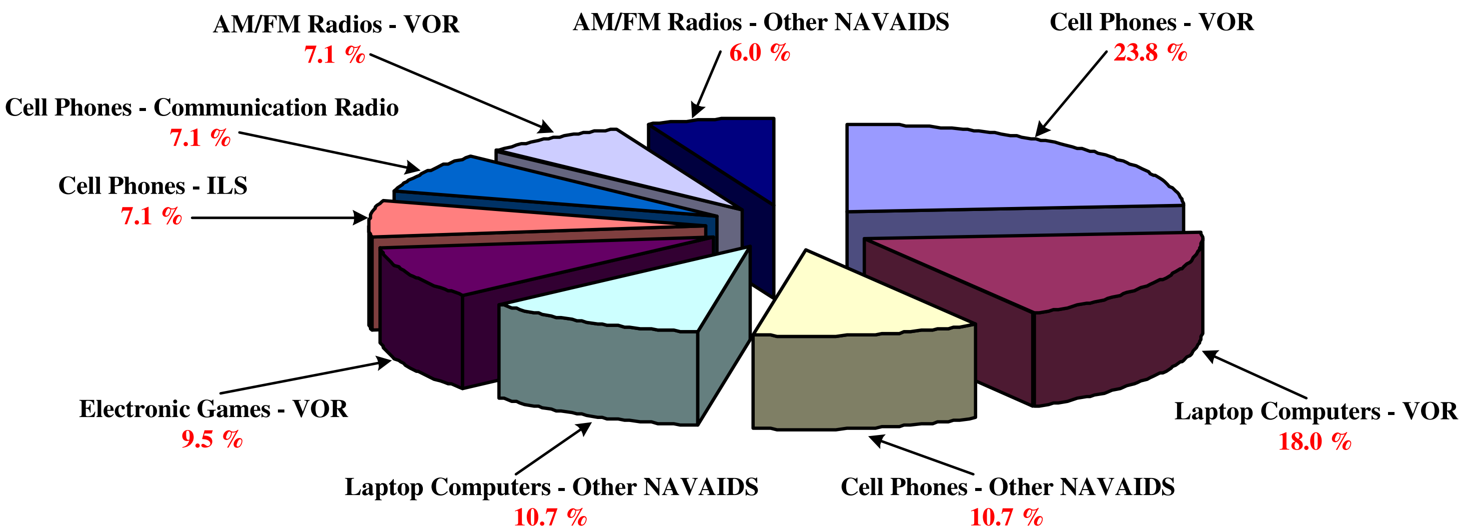


Figure-G.2 Percentage of a specific PED interfering with a specific avionic system

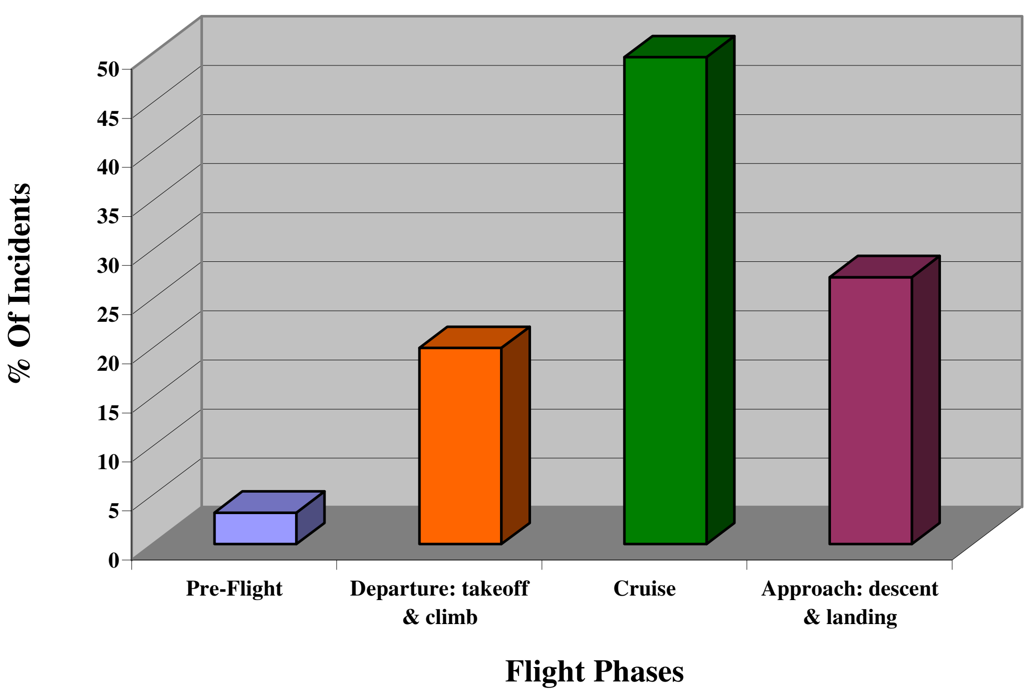
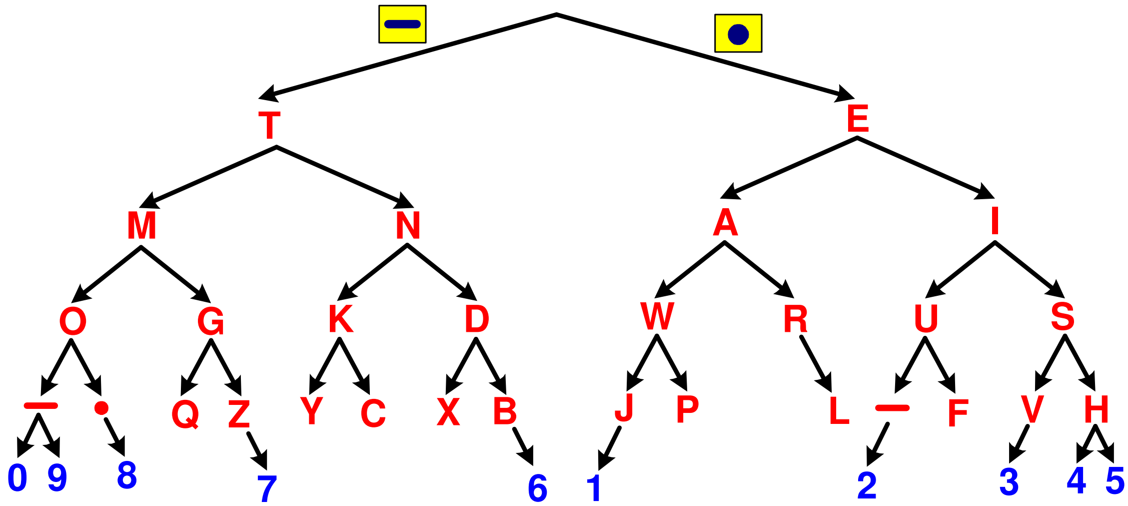


Figure-G.3 Flight phases associated with incidences

Appendix H: Morse code



Letters	Code
A	• —
B	— • • •
C	— • — •
D	— • •
E	•
F	• • — •
G	— — •
H	• • • •
I	• •
J	• — — —
K	— • —
L	• — • •
M	— —
N	— •
O	— — —
P	• — — •
Q	— — • —
R	• — •
S	• • •
T	—
U	• • —
V	• • • —
W	• — —
X	— • • —
Y	— • — —
Z	— — • •

No.	Code
0	— — — — —
1	• — — — —
2	• • — — —
3	• • • — —
4	• • • • —
5	• • • • •
6	— • • • •
7	— — • • •
8	— — — • •
9	— — — — •

Symbols	Code
period	• — • — • —
comma	— — • • — —
?	• • — — • •
/	— • • — •
@	• — — • — •

Figure-H.1 Morse code ***[K6-35]***

Appendix I: The importance of aerospace in the province of Québec and specifically in Montréal metropolitan

- *Almost all components to build an A/C can be found with 30 km radius.*

- *170 companies and facilities dedicated to the aerospace industry.*

- *Important Aerospace Companies:*

  - *Bombardier Aerospace*: 3rd largest manufacturer after Boeing and Airbus in the world.
  - *CAE Electronics:* World leader in flight simulators (85% of the world market).
  - *CMC Electronics:* One of the world leaders in avionics.
  - *Bell Helicopter Textron:* One of the world leaders in helicopters.
  - *Pratt & Whitney Canada*: World leader in aviation engines.
  - *Rolls Royce Canada:* World leader in maintenance and repair of engines.

- *The following international organizations have their head office in Montréal:*

  - UN's ICAO
  - IATA
  - International Federation of Air Traffic Controller's Associations (IFATCA)

- *Montreal is positioned as the 4th [2003] North American city in the aerospace industry.*

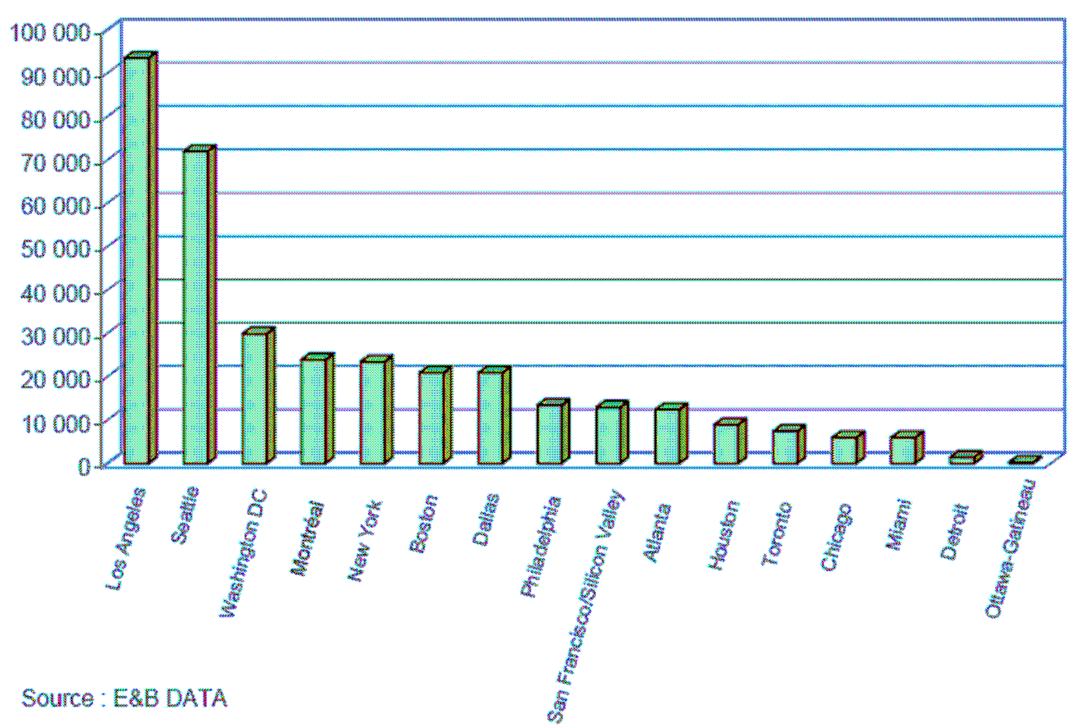


Figure-I.1 Aerospace in North American cities *[K4-13]*

Appendix J: Avionic related courses in Québec universities

Concordia University:

- ***ENGR-6461 Avionic Navigation Systems 4-Cr***
  Basics of modern electronic navigation systems, history of air navigation, earth coordinate and mapping systems; basic theory and analysis of modern electronic navigation instrumentation, communication and radar systems, approach aids, airborne systems, transmitters and antenna coverage; noise and losses, target detection, digital processing, display systems and technology; demonstration of avionic systems using flight simulator.

- ***ENGR-7461 Avionic Systems Design 4-Cr***
  Mechanics, analyses and design of advanced aerospace avionic systems; microwave landing systems, ADF, LORAN, GPS, VOR, TACAN, Airborne Radar and advanced Navigational Aids; electronics and basic design principles; electronic systems including air data computer; radar altimeter, specific energy computer for optimal flight profiles.

- ***ENGR-6421 Standards, Regulations and Certification 4-Cr***
  Overview of DoT and other international (FAA, etc.) aviation standards, regulations and certification procedures; regulatory areas, namely, pilot training/testing, air traffic procedures, aircraft systems design and airworthiness; development process for new regulations and criteria for certification.

École Polytechnique de Montréal:

- ***AE3-200 Caractéristiques de l'avion 2-Cr***
  Histoire de l'aviation. Types d'appareils de vol. Rappel de l'aérodynamique. Performances de l'avion. Stabilité et contrôle de l'avion. Structures. Chargement et contraintes. Procédure de certification. Moteurs et systèmes auxiliaires. Cabine de pilotage et vol aux instruments. Avionique. Systèmes mécaniques. Systèmes hydrauliques. Train d'atterrissage. Systèmes hypersustentateurs et de freinage. Espérance de vie de l'avion en fatigue. Procédure de design de l'avion.

- ***ELE-6209 Navigation aérienne 3-Cr***
  Types de systèmes de navigation. Équations de navigation. Mouvement sur une sphère. Effets dûs à la rotation de la terre. Estimation: matrice de covariance. Quaternions, plate-forme tri-axiale à cardans. Filtre de Wiener, échantillonnage, modélisation, algorithmes. Navigation inertielle avec ou sans plate-forme stabilisée. Système de positionnement global.

École de Technologie Supérieure:

- ***GPA-745 Introduction à l'avionique 3-Cr***
  Introduction aux systèmes électriques CA, CC : générateurs, batteries, filage, connecteurs, systèmes de bus Arinc 429, 629, et 636 (FDDI). Instruments de pilotage à l'atterrissage : localisateur, glissage, marqueur «beacon» et systèmes ILS et MLS pour indiquer l'azimut, l'élévation et la distance à l'aide de fréquences RF/VHF et micro-ondes. Systèmes de navigation par radio, radar et inertie pour la direction de vol (VOR, ADF) et pour l'aire de vol (RNAV). Positionnement par satellites (GPS) et systèmes de navigation (LORAN-C). Systèmes de radar pour la communication avec la tour de contrôle (ATCTX), alerte et collision, météo. Affichage électronique du cockpit, gyroscope et pilotage automatique.

- ***MGA-801 Contrôle et pilotage informatisé «Fly-by-Wire» 3-Cr***
  Notions de modélisation et de commande appliquées à l'avionique par la technique du «Fly-by-Wire». Le cours permettra aux étudiants de se familiariser notamment avec les différentes parties de l'avion, incluant les surfaces de contrôle et les instruments de vol, le modèle dynamique de l'avion, sa stabilité statique et dynamique et finalement le contrôle actif de vol, rendu possible grâce à la technologie «Fly-by-Wire». Modèle dynamique de l'avion : équations de mouvement rigide, variables d'orientation et de position, forces et moments appliqués à l'avion. Linéarisation du modèle non linéaire : modèle longitudinal, modèle latéral. Qualités de manoeuvrabilité : amortissement, dropback, marges de gain et de phase, largeur de bande, PIO. Design, analyse et simulation des systèmes de commande en navigation. Méthodes d'identification de la dynamique de vol d'un avion : commande linéaire, commande non linéaire. Analyse de stabilité : surfaces de contrôle longitudinal et latéral, stabilité statique, stabilité dynamique. Modèle d'optimisation du système de vol d'un avion. Optimisation des gains des régulateurs. echelonnement optimal de la commande sur l'enveloppe de vol.

McGill University:

- ***None.***

Université Laval:

- ***None.***

Université de Sherbrooke:

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K – Illustrations

Images: {Seen In Class Notes} & {Recreated Fully Using Visio}

[K1-1] ***Refer to [B1] Figure-17***

[K1-2] ***Refer to [B1] Figure-43***

[K1-3] ***Refer to [B1] Figure-60***

[K1-4] ***Refer to [B1] Figure-59***

Image: {Seen In Class Notes} & {Modified From the Original Using Visio}

[K2-1] ***Refer to [B6] Page-9-1A***

[K2-2] ***Refer to [B5] Page-1.35***

Images: {Seen In Class Notes} & {Recreated Fully Using Visio} & {Modified From the Original Using Visio}

[K3-1] ***Refer to [B1] Figure-6***

[K3-2] ***Refer to [B1] Figure-4***

[K3-3] ***Refer to [B1] Figure-12***

[K3-4] ***Refer to [B1] Figure-14***

[K3-5] ***Refer to [B1] Figure-16***

[K3-6] ***Refer to [B1] Figures-19 & 23***

[K3-7] ***Refer to [B1] Figure-37***

[K3-8] ***Refer to [B1] Figure-39***

[K3-9] ***Refer to [B1] Figure-40***

[K3-10] ***Refer to [B1] Figure-41***

[K3-11] ***Refer to [B1] Figure-42***

[K3-12] ***Refer to [B1] Figure-59***

[K3-13] ***Refer to [B1] Figure-77***

[K3-14] ***Refer to [B1] Figure-84***

[K3-15] ***Refer to [B1] Figure-87***

[K3-16] ***Refer to [B1] Figures-85 & 86***

[K3-17] ***Refer to [B1] Figure-92***

[K3-18] ***Refer to [B1] Figure-95***

[K3-19] ***Refer to [B1] Figure-115***

[K3-20] ***Refer to [B1] Figure-116***

[K3-21] ***Refer to [B1] Figure-120***

[K3-22] ***Refer to [B4] Notes-1 Slide-36***

[K3-23] ***Refer to [B4] Notes-2 Slide-39***

[K3-24] ***Refer to [B4] Notes-2 Slide-12***

[K3-25] ***Refer to [B1] Figure-128***

[K3-26] ***Refer to [B1] Figure-139***

[K3-27] ***Refer to [B3] Figure-2.1***

[K3-28] ***Refer to [B1] Figure-144***

[K3-29] ***Refer to [B1] Figure-145***

[K3-30] ***Refer to [B1] Figure-146***

[K3-31] ***Refer to [B4] Notes-1 Slide-73***

Images: {Seen On a Website}

[K4-1] ***http://terraserver.microsoft.com/About/AboutGlossaryLatlon.htm***

[K4-2] ***www.acespilotshop.com/images/products/headsets/new13x.jpg***

[K4-3] ***www.airwaysmuseum.com/NDB%20BLT%202-05.htm*** [similar]

[K4-4] ***http://en.wikipedia.org/wiki/Image:D-VOR_PEK.JPG***

[K4-5] ***http://www2.cytanet.com.cy/cyatsea/airport.htm***

[K4-6] ***www.tokai-bt.soumu.go.jp/musen/tyuubukokusai/img/borudeme_antena.jpg*** [similar]

[K4-7] ***http://bo777.hp.infoseek.co.jp/DSCF0128.JPG***

[K4-8] ***http://en.wikipedia.org/wiki/Image:VORTAC_TGO_Aichtal_Germany_01.JPG***

[K4-9] ***www.matematicamente.it/giochi/loran.jpg*** [similar]

[K4-10] ***www.imar-navigation.de/download/inertial_navigation_introduction.pdf***

[K4-11] ***www.vaisala.com/businessareas/instruments/products/visibility/lt31***

[K4-12] ***www.gitec-ph.com/IlocosDev/IlocosPic/Laoag%20DGPS%20survey%202.JPG***

[K4-13] ***Refer to [J2] Figure-2***

Images: {Seen On a Website} & {Modified From the Original Using Visio}

[K5-1] ***www.z-ksc.or.jp/img/vordme.jpg***

[K5-2] ***www.navfltsm.addr.com/ndb-nav-adf-1.htm***

[K5-3] ***www.harmon.com/hsi.htm***

[K5-4] ***Block-I: http://gorp.away.com/gorp/activity/hiking/skills/navigation/datum.htm***

Block-II: http://jbarker.com/school/courses/tc437/hx/documents/d000001.html

Block-IIA: www.wslfweb.org/docs/roadmap/irm/internet/dod/photos/gpsblk2.htm

Block-IIR & III: www.aero.org/publications/crosslink/summer2002/07.html

Block-IIR-M: www.globalsecurity.org/space/systems/images/blk2r-b.jpg

Block-IIF: www.kowoma.de/gps/Satelliten.htm

[K5-5] ***LOC-Tx: www.mlit.go.jp/koku/04_hoan/e/serv/radio/02.html***

GS^0-Tx: http://members.cox.net/firestation51/navaid.htm

MB-Tx: www.alaska.net/~chazmo/lynns.jpg

[K5-6] ***www.ent.ohiou.edu/~rthomas/mls.html***

[K5-7] ***www.srh.noaa.gov/srh/jetstream/atmos/layers.htm***

[K5-8] ***www.srh.noaa.gov/srh/jetstream/atmos/atmprofile.htm***

[K5-9] ***www.srh.noaa.gov/srh/jetstream/atmos/pvsh.htm***

Images: {Seen On a Website} & {Recreated Fully Using Visio} & {Modified From the Original Using Visio}

[K6-1] ***http://weather.org/singer/chapt02.htm***

[K6-2] ***http://kartoweb.itc.nl/geometrics/Map%20projections/body.htm***

[K6-3] ***www.asy.faa.gov/safety_products/airspacecard.html***

[K6-4] ***www.ivao.org/training/tutorials/Ipack/Files/L1-VFR-IFR.htm***

[K6-5] ***http://en.wikipedia.org/wiki/Image:Six_flight_instruments.JPG***

[K6-6] ***www.maritimeultralight.com/turnb.jpg***

[K6-7] ***www.gyrohouse.com/catalog/images/item558_1.jpg***

[K6-8] ***www.allstar.fiu.edu/aero/MagComp.htm***

[K6-9] ***www.allstar.fiu.edu/aero/NAVAIDS.htm***

[K6-10] ***http://copradar.com/preview/xappA/xappA.html***

[K6-11] ***https://ewhdbks.mugu.navy.mil/rdr-hori.htm***

[K6-12] ***http://cbdd.wsu.edu/kewlcontent/cdoutput/TR502/page21.htm***

[K6-13] ***www.allstar.fiu.edu/aero/ADF.htm***

[K6-14] ***Refer to [E6] Figure-3***

[K6-15] ***www.rvs.uni-bielefeld.de/publications/Reports/vor.gif***

[K6-16] ***www.allstar.fiu.edu/aero/RNAV.htm***

[K6-17] ***www.doc.ic.ac.uk/~nd/surprise_97/journal/vol1/jmd***

[K6-18] ***www.nels.org/loran/loran_system.htm***

[K6-19] ***www.lpi.ac-poitiers.fr/ancien_site/ateliers/aps/fr/pages/omega.html***

[K6-20] ***www.spawar.navy.mil/sti/publications/pubs/td/2627/fig3lg.gif*** &

http://en.wikipedia.org/wiki/Image:Laser_Ring_Gyro.PNG

[K6-21] ***Refer to [F8] Figure-A.2***

[K6-22] ***Refer to [F9] Figure-4.2***

[K6-23] ***Refer to [F8] Figure-3.2***

[K6-24] ***C/A, L2C, L5C: www.navcen.uscg.gov/gps/modernization/TheNewL2CivilSignal.pdf***

P(Y): http://geodesy.ceegs.ohio-state.edu/course/gs609/notes/Chap10%20final.pdf

M: www.mitre.org/work/tech_papers/tech_papers_00/betz_overview/betz_overview.pdf

[K6-25] ***www.space.gc.ca/asc/img/apogee_0604_spaceops_gps.jpg***

[K6-26] *ftp://tycho.usno.navy.mil/pub/gps/gpsb1.txt* & *ftp://tycho.usno.navy.mil/pub/gps/gpsb2.txt*

[K6-27] *www.trimble.com/gps/errorsources.html*

[K6-28] *www.navfltsm.addr.com/ils.htm*

[K6-29] *www.faa.gov/ATpubs/AIM/Chap2/aim0201.html*

[K6-30] *http://en.wikipedia.org/wiki/Runway*

[K6-31] *http://upload.wikimedia.org/wikipedia/en/7/79/ILS_illustration.jpg*

[K6-32] *http://en.wikipedia.org/wiki/Microwave_Landing_System*

[K6-33] *www.airwaysmuseum.com/MLS%20Interscan%20article%20Stern%2078.htm*

[K6-34] *www.globalsecurity.org/space/library/report/1996/image1099.gif*

[K6-35] *www.learnmorsecode.com*