DOCUMENT

**GSM-G-CPL.016**

DOCUMENT TITLE

# FLIGHT INSTRUMENTS

# CHAPTER 16 – INERTIAL NAVIGATION SYSTEMS

Version 1.0

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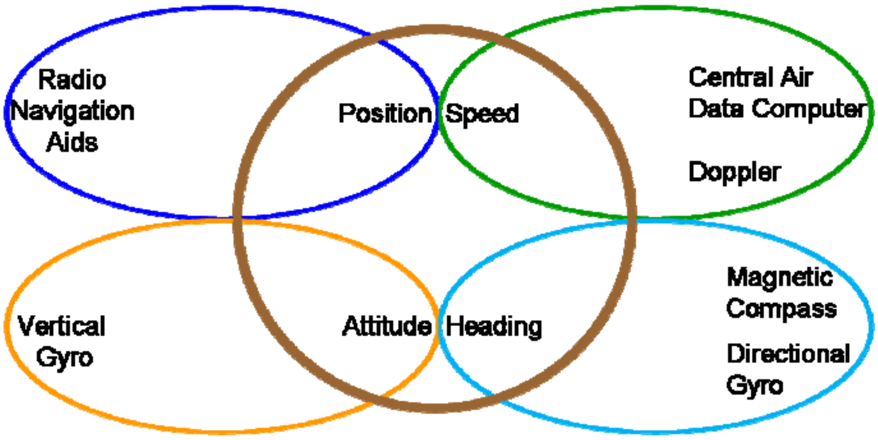
# INERTIAL NAVIGATION SYSTEMS

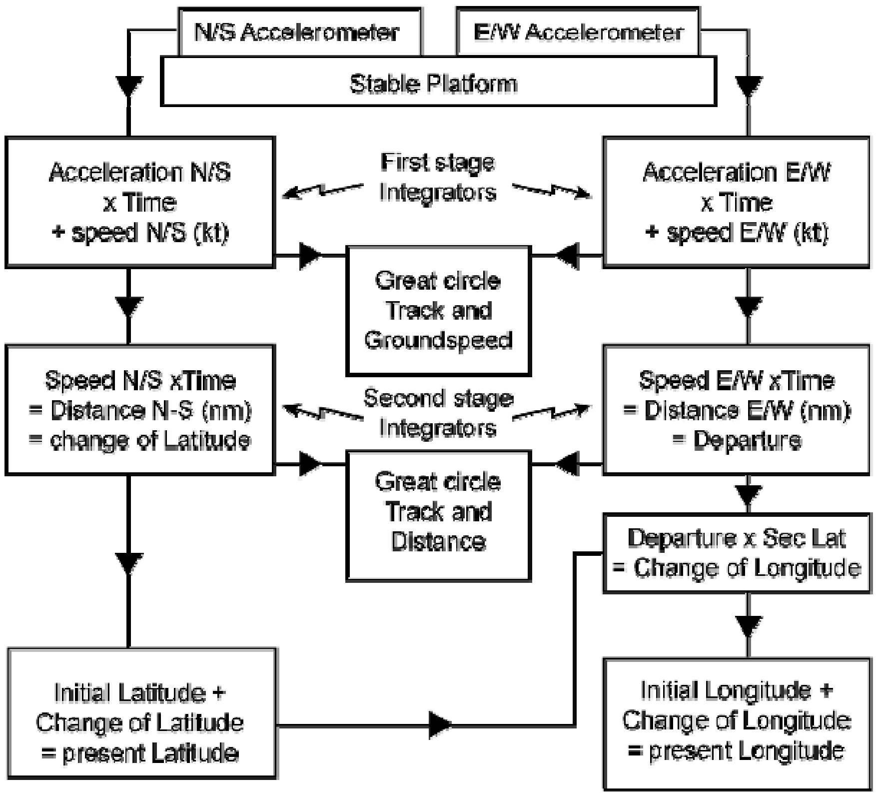
## INTRODUCTION

An Inertial Navigation System (INS) is entirely self-contained and provides world-wide navigation information independently of external aids. Navigation information is only part of the output of the inertial system. Outputs include functions of attitude, heading, acceleration, angular rates, track angle, groundspeed, wind data and position.




## PRINCIPLE OF INERTIAL NAVIGATION

The INS must be given a starting reference point in order to calculate all other information. When provided with accurate ramp co-ordinates (latitude and longitude) the INS can align itself and all further navigational calculations are based on this initial position. Change of position is computed from the outputs from two acceleration measuring devices (accelerometers) monitored along axes at 90$^{O}$ to each other. Commonly the alignment of accelerometers is North/South and East/West. Some systems include a third accelerometer aligned to sense vertical acceleration. Using this output, vertical speed and altitude can be computed.



It should be noted that only aircraft accelerations are sensed and from these values are computed velocity, distance travelled and change of position.

**INITIAL POSITION + CHANGE OF POSITION = PRESENT POSITION**

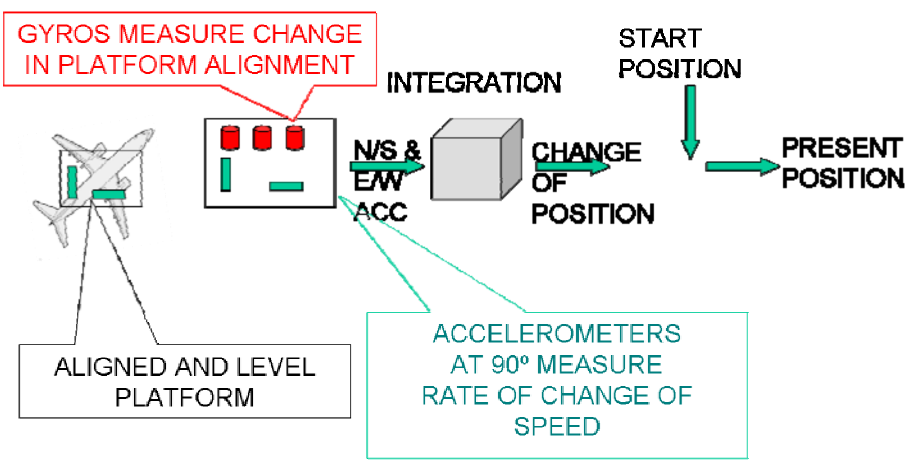
The process of measuring aircraft acceleration is complex because the aircraft has movement in pitch, roll and yaw and flies above the surface of the earth which is itself rotating and moving through space. Angular displacement is measured by mechanical rate gyros, displacement gyros or ring laser gyros. A computer determines corrections to accelerometer outputs based on angular displacement and other factors to isolate aircraft horizontal and vertical accelerations.

There are two methods of compensating for aircraft attitude changes and movement in space:

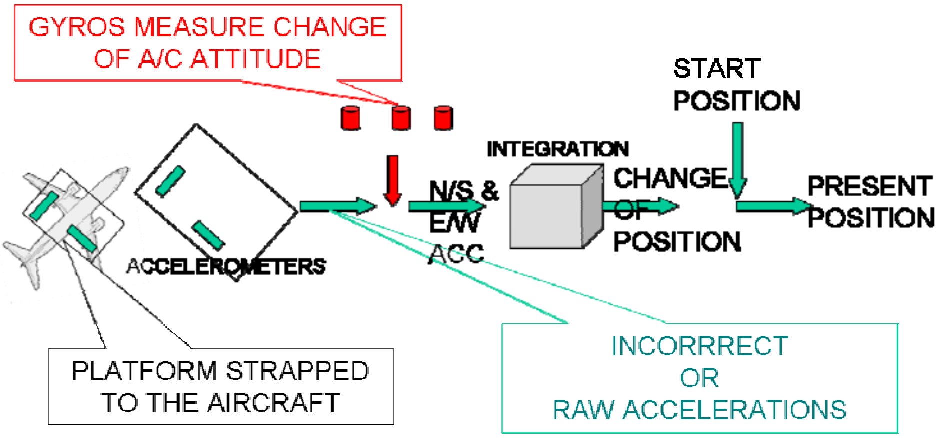
1. Mounting the accelerometers on a **'stable platform'.** The platform is gimbal mounted so that it can be kept horizontal to the Earth's surface and correctly aligned with the local meridian. Corrections are generated by sensing gyros on the platform which control motors between the gimbals and the aircraft. The INS computer develops further corrections for movement in space and over the earth.

2. **'Strapping-down'** the accelerometers and sensing gyros to the aircraft structure. In such systems, the accelerometers sense all acceleration, including those in pitch, roll and yaw of the aircraft.

The outputs of accelerometers mounted on a stable platform are N/S and E/W components of acceleration which can directly be converted into change of position. However, 'strap-down' accelerometers provide raw data which require computer corrections before they can be used as components of horizontal acceleration. Strap-down systems are referred to as IRS (Inertial Reference Systems).



STABLE PLATFORM INS

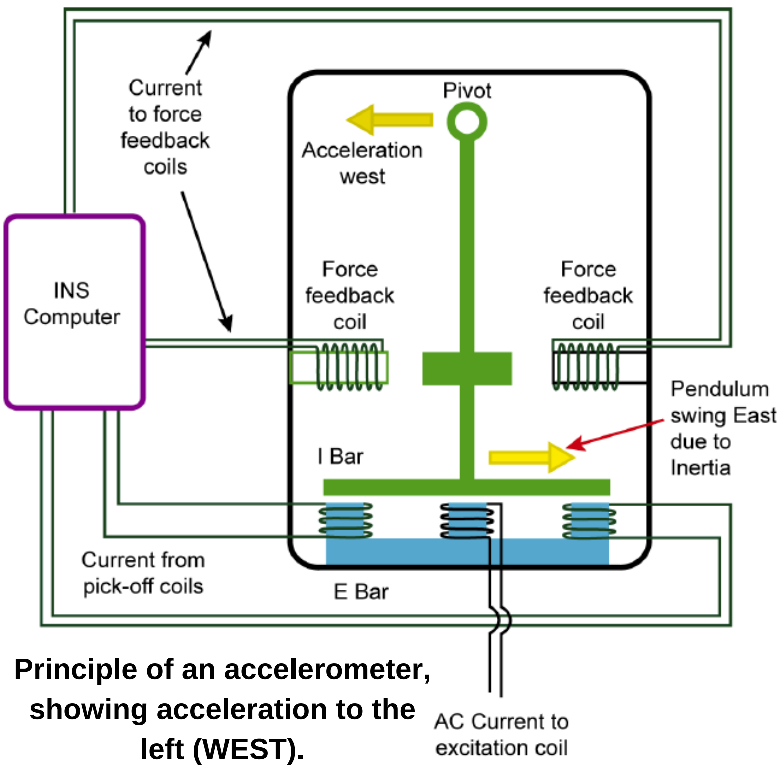



STRAPDOWN IRS

## ACCELEROMETERS

Accelerometers are designed to accurately measure aircraft accelerations along defined axes. The most common type works on the principle of force balance, i.e. acceleration can be measured from the amount of restoring force required to keep a pendulum vertical.

The pivot of the pendulum allows it to swing along one alignment axis only eg. N/S or E/W. The greater the acceleration along the swing axis the more the pendulum swings from the vertical as it lags behind the pivot.




**Principle of an accelerometer, showing acceleration to the left (WEST).**

Movement of the pendulum is then sensed, typically by E and I bars similar to those found in servo altimeters. The E bar is fixed to the stable platform with its legs pointing up and the I bar lies horizontally above it, fixed to the bottom of the pendulum. Movement of the pendulum takes the I bar out of the horizontal, upsets the gaps between E and I bars and causes an error signal to be generated. This signal is fed to the INS computer which then feeds current to the feed-back coils to pull the pendulum back to the vertical keeping the I bar parallel to the E bar. The strength of the current needed to achieve this is directly proportional to the acceleration and is used by the computer to measure the acceleration along the swing axis of the accelerometer. The extreme sensitivity of such a system enables it to detect the smallest of accelerations.

**Accelerometer characteristics:**

- Low Sensitivity Threshold $10^{-6}$g
- Wide Sensitivity Range -10 to +10g
- High Accuracy $\pm$.001%
- Shock Proof (withstands up to 60 g)

In 'stable platform' INS, accelerometers are kept aligned North-South and East-West. In 'strap-down' IRS, accelerometers measure acceleration relative to the aircraft's axes.

## INTEGRATION

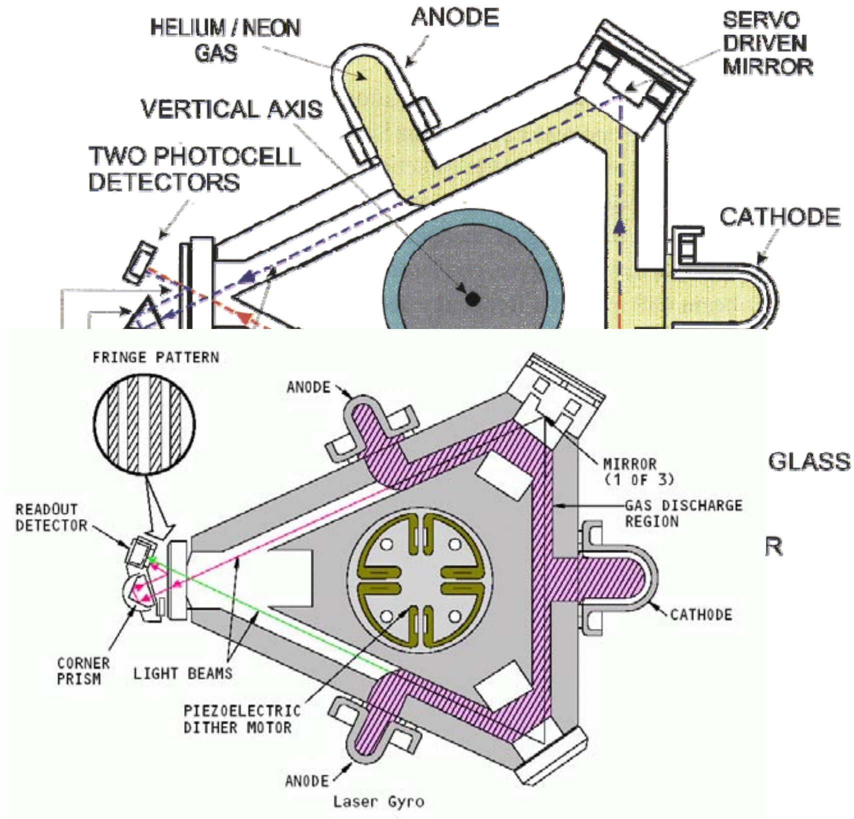
At the first stage of integration, the output of the accelerometers is integrated with respect to time to obtain speed. At the second stage, speed is integrated with respect to time to obtain distance travelled. Integration can be thought of as the process of the addition of all the small changes in acceleration or speed during infinitely short periods of time to obtain their present values. In the case of the stable platform, the outputs of the second stage of integration are N/S and E/W components of distance travelled. Distance N/S in nautical miles equates to change of latitude in minutes and when applied to initial latitude, leads to present latitude. Distance E/W requires an input of the secant of the latitude to obtain change of longitude. When applied to initial longitude, present longitude is obtained.

## GYROSCOPIC DISPLACEMENT MEASUREMENT

Both 'stable platform' and 'strap-down' systems require gyros to measure rates of angular rotation. In the case of stable platforms, gyro outputs are fed to gimbal motors to restore the displaced platform to its level and aligned position. Strap-down systems use gyro outputs to compute the required corrections to raw accelerometer data.

It should be noted that inertial systems use either mechanical rate gyros or ring laser gyros to measure angular rates and platforms are not stabilized through gyroscopic rigidity.

Ring laser gyros do not have spinning rotors and so have little in common with mechanical gyros. Nevertheless they measure angular displacement and so are considered to be ‘gyro like’ devices.




The ring laser gyro uses two beams of <u>coherent</u> (in phase) light travelling in opposite directions along a triangular or square chamber, at the corners of which are reflecting mirrors. When the gyro is rotated about an axis perpendicular to the light path, one beam has slightly further to travel and the other slightly less. By altering the "chamber length", a change of frequency is achieved, The difference in frequency between the two beams produces an interference pattern from which angular rotation is measured.

Compared to mechanical gyros, ring laser gyros have the following advantages:

1. Reduced alignment times.
2. Improved accuracy.
3. Higher reliability.
4. Smaller size.
5. Lower power consumption.

At very low rates of rotation, there is a tendency for the two beams to lock into the same frequency giving a zero output. The problem, known as ‘laser lock’, is overcome by oscillating the gyro rapidly about its sensitive axis, a method known as “dithering”. Consequentially the laser gyro is sensitive to low dynamic rates (of angular rotation) while also being insensitive to ‘g’.

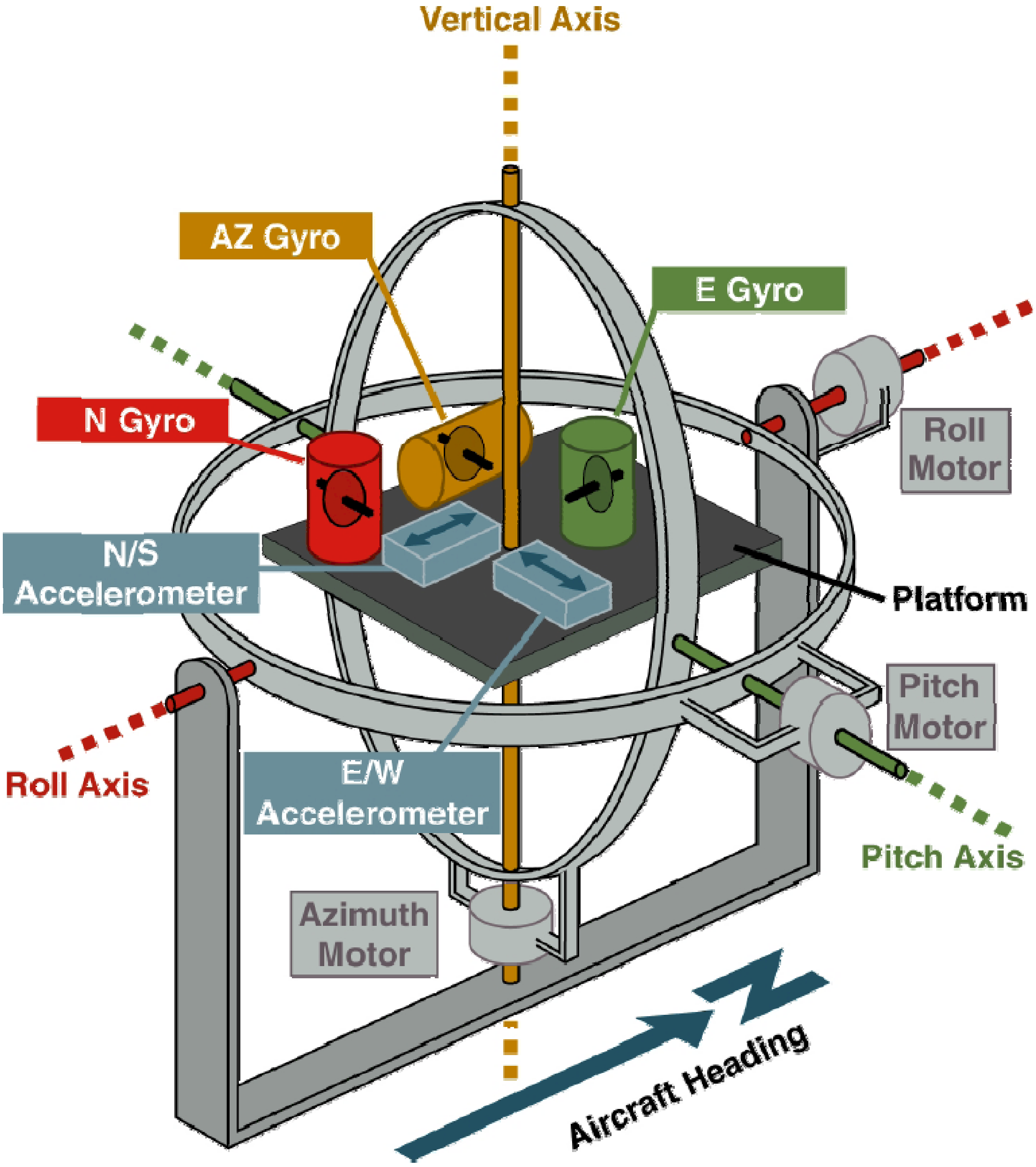
The accuracy of a laser beam is affected by the length of its optical path. The relationship between length and accuracy is non-linear and a small increase in length, say 10%, will result in a significant improvement in accuracy, say 25%.

While the laser gyro does not contain mechanical moving parts, it does like its mechanical equivalent suffer from random drift. In the laser gyro, this is caused by noise which is likely to be due to imperfections in the mirrors

INS uses three laser or mechanical gyros:

- One Azimuth Gyro to sense any movement of the platform in azimuth.
- Two Tilt Gyros to sense North/South or East/West tilt of the platform.

The latest 'strap-down' inertial systems use laser gyros but mechanical gyros could be used. Strap-down systems and laser gyros are parallel technical developments, one not being dependent on the other.

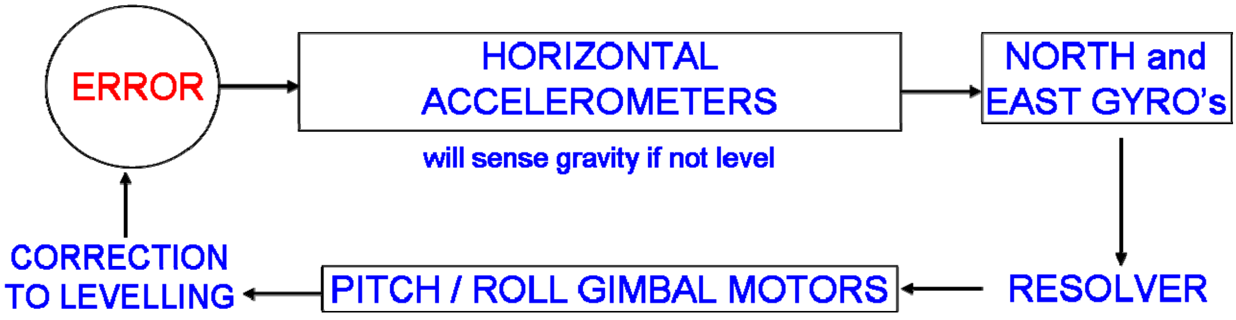



EXAMPLE OF STABLE PLATFORM INS

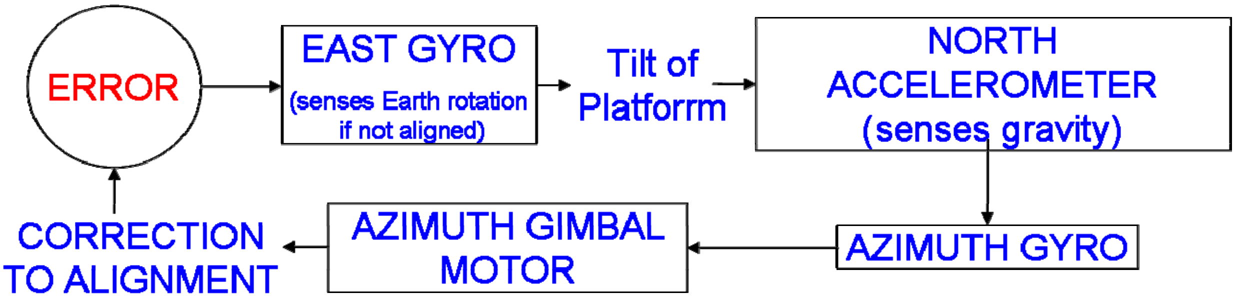
## INITIAL LEVELLING AND ALIGNMENT

The process of levelling and alignment must be carried out on the ground with the aircraft stationary. With older systems, the process takes about 15 minutes, but the latest IRS, equipped with ring laser gyros, can complete alignment in about 5 minutes.

Initial levelling is achieved by monitoring the output of the accelerometers. Any output with the aircraft stationary is the result of a component of gravity sensed when the accelerometers are not level. The accelerometer outputs are used as error signals to bring about fine levelling.




Initial azimuth alignment is achieved by monitoring the output of the EAST (North/South tilt sensing) gyro. With the aircraft stationary, any tilt that is sensed by this gyro is due to earth rotation. As earth rotation has a zero component in the North/South plane, the tilt sensed is due to misalignment. The correction for tilt causes a signal to be produced by the N/S accelerometer which is then fed to the azimuth gimbal motor. The platform is then adjusted in azimuth until the signal is cancelled. This process of fine alignment is known as "gyro-compassing". (To prevent oscillations, corrections take place outside of the Schuler loop, which is described later in this chapter.)

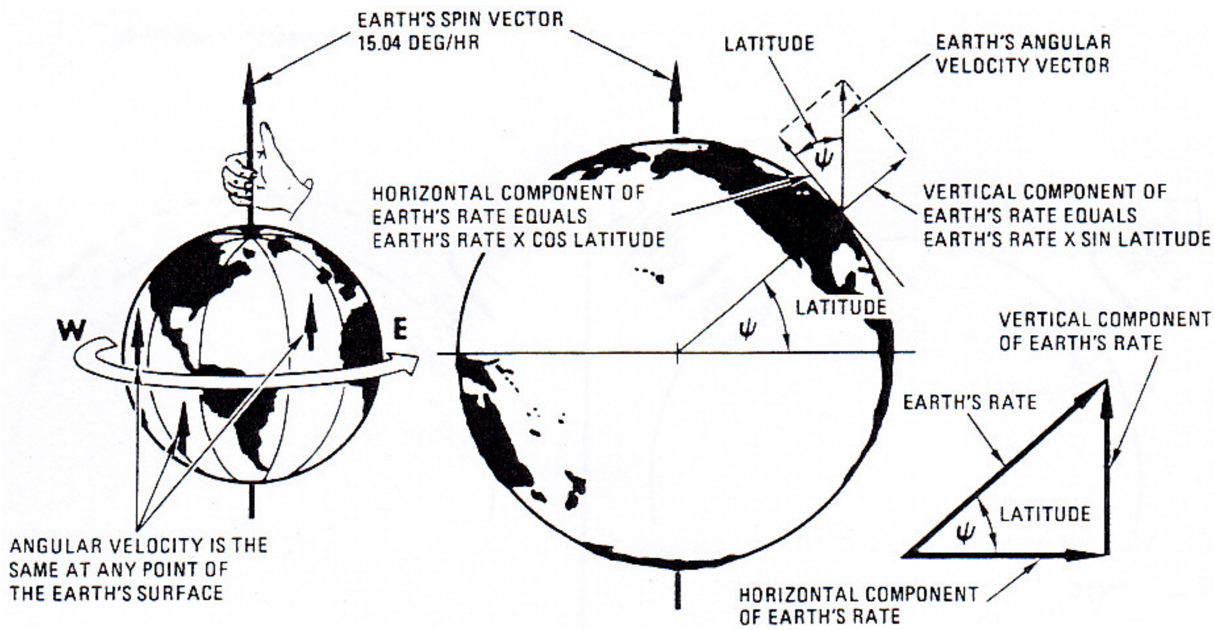



Even on the ground, correct levelling and alignment can only be maintained if corrections are continuously applied for Earth rotation. These corrections depend on latitude and if the ramp position is incorrectly set, the INS will fail to enter the NAV mode and navigation information will be unavailable. The INS will reject the ramp position if the latitude is set in error by 30' (30nm) or more. The INS will accept an incorrectly set longitude.

## CORRECTIONS IN-FLIGHT

In flight, corrections to alignment and levelling are required to take into account earth rotation and transport. These correction rates, which vary with latitude, are applied to the gyros to trigger realignment and relevelling of the platform by means of the gimbal motors.

Corrections are also required for Coriolis effect (curved path of the aircraft in space) and for the aircraft's angular velocity. These corrections are applied to the accelerometers.



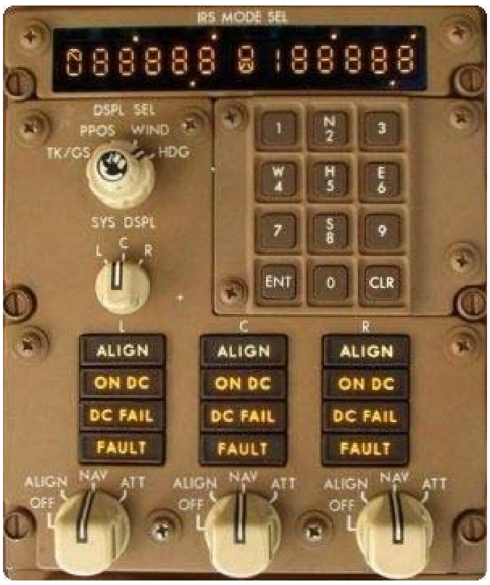

| AXIS | GYRO'S | | ACCELEROMETERS | |
|---|---|---|---|---|
| | Earth Rate | Transport Wander | Centripetal Force | Coriolis Effect |
| **North** | $\Omega \cos \lambda$ | $\frac{U}{R}$ | $-\frac{U^2 \tan \lambda}{R}$ | $-2\,\Omega\, U \sin \lambda$ |
| **East** | Nil | $-\frac{V}{R}$ | $\frac{UV \tan \lambda}{R}$ | $2\,\Omega\, V \sin \lambda$ |
| **Azimuth/ Vertical** | $\Omega \sin \lambda$ | $\frac{U \tan \lambda}{R}$ | $\frac{U^2 + V^2}{R}$ | $2\,\Omega\, U \cos \lambda$ |

V = Velocity North
U = Velocity East
λ = Latitude
R = Radius of the Earth
Ω = Earth Rotation (15.04°/hr)

## TYPICAL SYSTEM

A typical system will have the following units:

### NAV UNIT

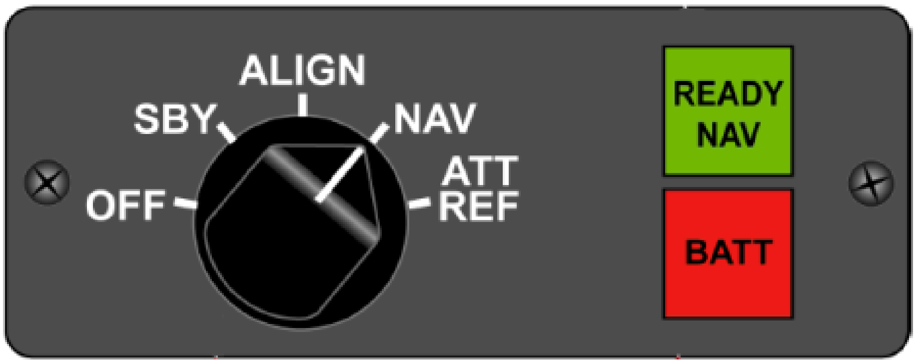



The Nav Unit contains the platform on which the accelerometers and gyros are mounted and also the digital computer.

### MODE SELECTOR UNIT (MSU)

The MSU is in the overhead panel. It is used to switch on and to align the INS prior to push-back. The Attitude mode is a down-graded mode of operation which may be selected in flight to restore attitude and heading outputs in the event of failure of NAV function. The 747-400 has a single MSU panel to control three inertial reference units.

## MODE SELECTOR SWITCH




This selects operating modes of the INS:

- ALIGN: Selecting align causes the INS to go through the alignment process to make the INS ready to navigate
- NAV: The NAV position is used for normal operation after alignment is complete. The NAV mode must be selected and the system verified to be in NAV before moving the aircraft.
- ATT: When operating in the ATT mode, the computer is shut down. The alignment reference is lost and the NAV mode cannot be selected until the system is automatically aligned on the ground.

It should be noted that moving the Mode Selector Switch out of NAV in flight will cause the alignment to be lost. Navigation functions will not be regained until the platform is next realigned on the ground.

## READY NAV INDICATOR

This lights green to annunciate alignment conditions are complete. The aircraft can now be moved.

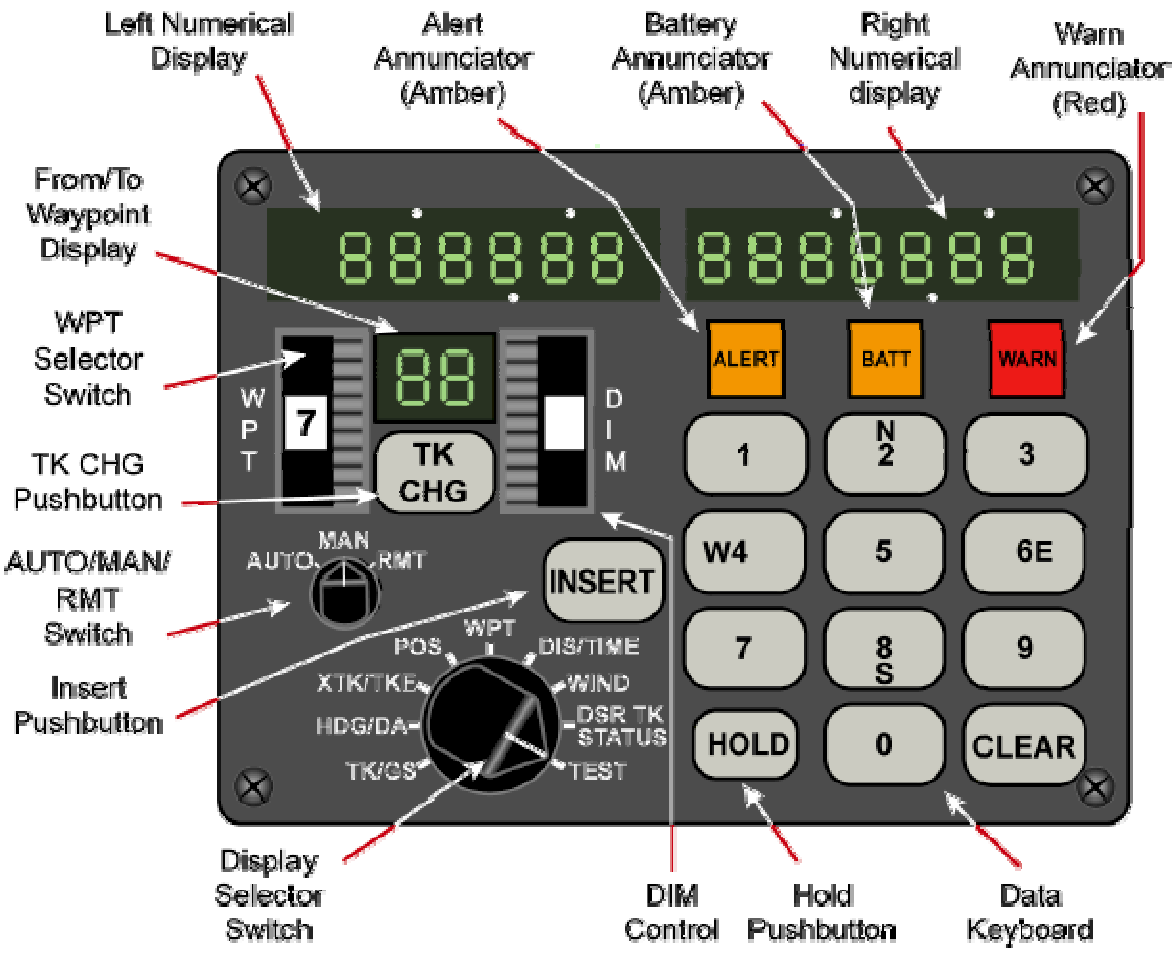
## BAT INDICATOR

This lights red if INS has shutdown while operation on battery power, thus indication low battery charge.

## BATTERY UNIT

The battery unit is used to power the INS during any interruptions of power supply. The battery can run the INS for about 30 minutes.

## CONTROL DISPLAY UNIT (CDU)




The CDU is in the central console and permits control and display of navigation information. It provides the interface of communicating link between the pilot and the computer.

1. **AUTO/MAN/RMT SWITCH -** selects automatic leg switching by the INS (AUTO) or manual leg switching by the pilot (MAN). RMT (remote) allows a single CDU to load waypoint data, DME data and manual position fix data into all operating INS units (on some units might be a pushbutton which lights amber when activated).

2. **TEST SWITCH -** when pressed, causes all indicators on CDU and MSU to light and all displays to show 8's.

3. **DISPLAY SELECTOR SWITCH -** selects CDU data displays (more info below).

4. **DIM SWITCH -** controls light intensity of the data displays, the FROM -TO display, and the ALERT, HOLD, REMOTE, INSERT, and WY PT CHG indicators.

5. **TK CHG KEY -** allows numbers in FROM/TO display to be changed (track change). Key lights when activated.

6. **WAYPOINT/DME SELECTOR SWITCH (THUMBWHEEL SWITCH) -** selects waypoint number or DME station number for data displays.

7. **FROM -TO DISPLAY -** two non-flashing numbers display the waypoints defining the current navigation leg. A single flashing number defines the DME station which has been designated for the update.

8. **HOLD KEY -** used to freeze displayed position, to perform manual position update, and to display the non-updated (inertial) position. Key lights when activated.

9. **LEFT AND RIGHT DATA DISPLAYS -** displays data from INS computer as selected by the data selector switch.

10. **INSERT KEY -** inserts loaded data into the computer. It normally lights while data is being loaded into CDU and goes out when pressed to insert data into the INS computer.

11. **ALERT INDICATOR -** lights amber two minutes before airplane reaches waypoint during flight. In MAN the light will flash as the waypoint is passed and will continue to do so until the the waypoint change is made manually. In AUTO the Automatic Flight Control System (AFCS) will make the necessary track change at the waypoint, the light will go out and the INS will change the FROM-TO display.

12. **BAT INDICATOR -** lights amber when INS is operating on battery power.

13. **WARN INDICATOR -** lights red when INS detects an abnormal condition, eg. a parameter out-of-tolerance. Selection of STS (system status) - allows code numbers to be read which identifies the malfunction (see next page).

14. **KEYBOARD (KEYS 0 THROUGH 9) -** consists of 10 keys to load data into data displays and FROM TO displays.

15. **CLEAR KEY -** used to cancel a data loading operation prior to pressing INSERT.

## THE DISPLAY SELECTOR SWITCH

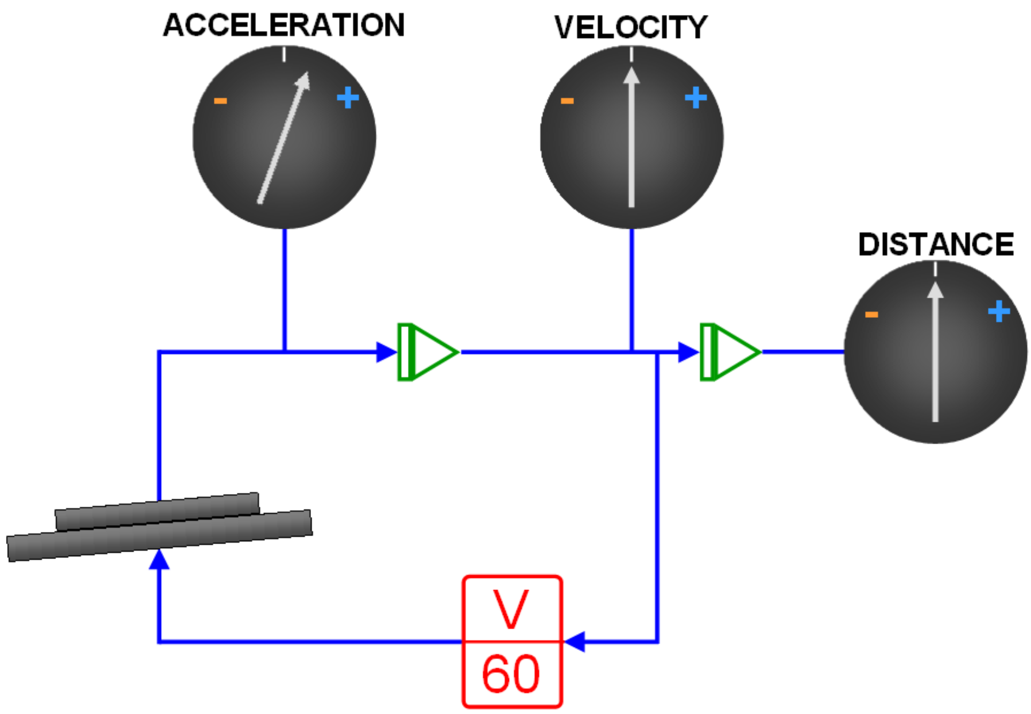
The Display Selector controls the read out in the Left and Right Display Panels at the top of the CDU.

| DATA SELECTOR POSITION | LEFT DISPLAY PANEL | RIGHT DISPLAY PANEL |
|---|---|---|
| **TK/GS** | Present Track (T) to the nearest tenth of a degree. | Present Groundspeed, to the nearest knot. |
| **HDG/DA** | Present Heading (T) to the nearest tenth of a degree. | Drift Angle, left or right of heading to the nearest degree. |
| **XTK/TKE** | Cross Track Distance, left or right of desired track, to the nearest tenth of a nm. | Track Angle Error, left or right of desired track, to the nearest degree. |
| **POS** | Present Position, to the nearest tenth of a minute of latitude. | Present Position, to the nearest tenth of a minute of longitude. |
| **WAY PT** | Waypoint Position, to the nearest tenth of a minute of latitude. | Waypoint Position, to the nearest tenth of a minute of longitude. |
| **DIS/TIME** | Great Circle Distance, to the nearest nm | Time, to the nearest tenth of a minute at present ground speed. |
| **WIND** | Wind Direction (T), to the nearest degree (dependent on ADC input). | Wind Speed, to the nearest knot. |
| **DSRTK/STS** | Desired (Initial) Great Circle Track between the two waypoints in the FROM/TO display, to the nearest degree (T). | System Status - action/malfunction codes |

A check can be made to ensure that waypoint coordinates have been correctly inserted by selecting the waypoint numbers on the FROM-TO display and then DIS/TIME followed by DSRTK/STS on the data selector switch. The distance (DIS) and track direction (DSRTK) displayed should correspond with the figures shown on the flight plan.

## SCHULER LOOP

An inertial platform maintained level with the surface of the earth behaves like a pendulum of length equal to the radius of the earth. The period of oscillation of a pendulum when disturbed can be calculated from its length and in this case, the period is 84.4 minutes. It can be observed that certain errors in the IN are cyclical, ie. they oscillate about a mean rather then increase with time, and their cycle period corresponds to that of the pendulum just described.




Errors that cycle between maximum values in each direction do so because they exist within a loop of correction and over-correction. This is referred to as a "Schuler Loop". Errors within a Schuler Loop do not increase with time and so are described as BOUNDED.

## BOUNDED AND UNBOUNDED ERRORS

The sources of BOUNDED and UNBOUNDED errors are as follows:-

| | |
|---|---|
| **1.** INACCURATE ACCELEROMETER | BOUNDED |
| **2.** INITIAL LEVELLING ERROR | BOUNDED |
| **3.** INACCURATE 1ST STAGE INTEGRATOR | BOUNDED |
| **4.** INACCURATE 2ND STAGE INTEGRATOR | UNBOUNDED |
| **5.** INITIAL MISALIGNMENT IN AZIMUTH | UNBOUNDED |
| **6.** AZIMUTH AND LEVELLING GYRO DRIFT ***** | UNBOUNDED |

***NOTE**: gyro drift is the major source of unbounded error.

## RADIAL ERROR RATE

Inertial systems accumulate error during flight and on landing it is possible to calculate the error rate per hour (radial error rate) by comparing the INS position with the position where the aircraft is parked.

$$\textbf{Radial error rate (nm per hour)} = \frac{\textbf{Distance INS position to Ramp Position (nm)}}{\textbf{Time spent in NAV mode (hours)}}$$

The example below illustrates the calculation, but note that a fully serviceable inertial system may have an error rate as little as ½ nm per hour.

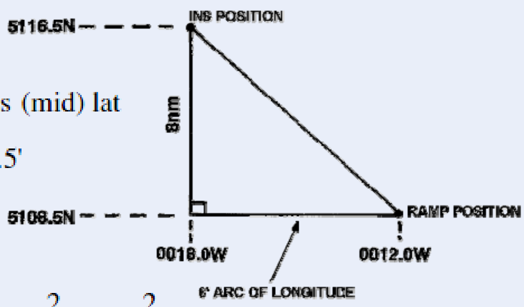
### EXAMPLE

Following a flight from New York to London the INS showed a position of 51° 16.5'N 00°18.0'W when the aircraft was stationary on the ramp at London Gatwick. The ramp position was given as 51° 08.5'N 00° 12.0'W. The time in the navigation mode was 5 hours and 24 minutes. Using this information determine the INS radial error rate.

### SOLUTION

Whilst the INS computer bases all calculations on spherical trigonometry, the human solution of radial rate error can be achieved to a satisfactory degree of accuracy using two-dimensional trigonometry.

The distance in longitude between the INS position and the ramp position is calculated using the departure formula:




$$\text{distance (nm)} = \text{d long (')} \times \cos\text{ (mid) lat}$$

$$= 6 \times \cos 51°12.5'$$

Using Pythagoras:

$$\text{distance ramp to INS position}^2 = 8^2 + 3.76^2$$

$$= 78$$

$$\text{distance ramp to INS position} = \sqrt{78}$$

$$= 8.8 \text{ nm}$$

$$\text{the radial error rate} = \frac{8.8 \text{ nm}}{5.4 \text{ hrs}}$$

$$= 1.63 \text{ nm/hr}$$