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SCHOOL OF MECHANICAL ENGINEERING

DEPARTMENT OF AERONAUTICAL ENGINEERING

UNIT – I - ROCKETS SYSTEM – SAE1402

I. Ignition System

An ignition system is a system for igniting a fuel-air mixture. Ignition systems are well known in the field of internal combustion engines such as those used in petrol (gasoline) engines used to power the majority of motor vehicles, but they are also used in many other applications such as in oil-fired and gasfired boilers, rocket engines, etc. Diesel engines rely on air compression for ignition, but usually also have glow plugs that preheat the combustion chamber to allow starting of the engine in cold weather. Other engines may use a flame, or a heated tube, for ignition.

Types

1. Magneto systems
2. Switchable systems
3. Battery and coil-operated ignition
4. Modern ignition systems
5. Mechanically timed ignition
6. Electronic ignition
7. Digital electronic ignitions

Magneto systems

Magneto ignition coil. For more details on this topic, see Ignition magneto. The simplest form of spark ignition is that using a magneto. The engine spins a magnet inside a coil, or, in the earlier designs, a coil inside a fixed magnet, and also operates a contact breaker, interrupting the current and causing the voltage to be increased sufficiently to jump a small gap. The spark plugs are connected directly from the magneto output. Early magnetos had one coil, with the contact breaker (sparking plug) inside the combustion chamber. In about 1902, Bosch introduced a double-coil magneto, with a fixed sparking plug, and the contact breaker outside the cylinder. Magnetos are not used in modern cars, but because they generate their own electricity they are often found on piston-engined aircraft engines and small engines such as those found in mopeds, lawnmowers, snowblowers, chainsaws, etc. where a battery-based electrical system is not present for any combination of necessity, weight, cost, and reliability reasons. Magnetos were used on the small engine's ancestor, the stationary "hit and miss" engine which was used in the early twentieth century, on older gasoline or distillate farm tractors before battery starting and lighting became common, and on aircraft piston engines. Magnetos were used in these engines because their simplicity and self-contained operation was more reliable, and because magnetos weighed less than having a battery and dynamo or alternator.

Aircraft engines usually have dual magnetos to provide redundancy in the event of a failure, and to increase efficiency by thoroughly and quickly burning the fuel air mix from both sides towards the center. The Wright brothers used a magneto invented in 1902 and built for them in 1903 by Dayton, Ohio inventor, Vincent Groby Apple.[1] Some older automobiles had both a magneto system and a battery actuated system (see below) running simultaneously to ensure proper ignition under all conditions with the limited performance each system provided at the time. This gave the benefits of easy starting (from the battery system) with reliable sparking at speed (from the magneto). Switchable systems Switchable magneto ignition circuit, with starting battery. The output of a magneto depends on the speed of the engine, and therefore starting can be problematic. Some magnetos include an impulse system, which spins the magnet quickly at the proper moment, making easier starting at slow cranking speeds. Some engines, such as aircraft but also the Ford Model T, used a system which relied on non rechargeable dry cells, (similar to a large flashlight battery, and which was not maintained by a charging system as on modern automobiles) to start the engine or for starting and running at low speed. The operator would manually switch the ignition over to magneto operation for high speed operation. To provide high voltage for the spark from the low voltage batteries, a 'tickler' was used, which was essentially a larger version of the once widespread electric buzzer. With this apparatus, the direct current passes through an electromagnetic coil which pulls open a pair of contact points, interrupting the current; the magnetic field collapses, the spring-loaded points close again, the circuit is reestablished, and the cycle repeats rapidly. The rapidly collapsing magnetic field, however, induces a high voltage across the coil which can only relieve itself by arcing across the contact points; while in the case of the buzzer this is a problem as it causes the points to oxidize and/or weld together, in the case of the ignition system this becomes the source of the high voltage to operate the spark plugs. In this mode of operation, the coil would "buzz" continuously, producing a constant train of sparks.

The entire apparatus was known as the 'Model T spark coil' (in contrast to the modern ignition coil which is only the actual coil component of the system). Long after the demise of the Model T as transportation they remained a popular self-contained source of high voltage for electrical home experimenters, appearing in articles in magazines such as Popular Mechanics and projects for school science fairs as late as the early 1960s. In the UK these devices were commonly known as trembler coils and were popular in cars pre-1910, and also in commercial vehicles with large engines until around 1925 to ease starting. The Model T (built into the flywheel) differed from modern implementations by not providing high voltage directly at the output; the maximum voltage produced was about 30 volts, and therefore also had to be run through the spark coil to provide high enough voltage for ignition, as described above, although the coil would not "buzz" continuously in this case, only going through one cycle per spark. In either case, the low voltage was switched to the appropriate spark plug by the 'timer' mounted on the front of the engine. This performed the equivalent function to the modern distributor, although by directing the low voltage, not the high voltage as for the distributor. The timing of the spark was adjustable by rotating this mechanism through a lever mounted on the steering column. As the precise timing of the spark depends on both the 'timer' and the trembler contacts within the coil, this is less consistent than the breaker points of the later distributor. However, for the low speed and the low compression of such early engines, this imprecise timing was acceptable.

Battery and coil-operated ignition

Inductive discharge ignition With the universal adoption of electrical starting for automobiles, and the availability of a large battery to provide a constant source of electricity, magneto systems were abandoned for systems which interrupted current at battery voltage, using an ignition coil (a transformer) to step the voltage up to the needs of the ignition, and a distributor to route the ensuing pulse to the correct spark plug at the correct time. The first reliable battery operated ignition was developed by the Dayton Engineering Laboratories Co. (Delco) and introduced in the 1910 Cadillac. This ignition was developed by Charles Kettering and was a wonder in its day. It consisted of a single coil, points (the switch), a capacitor and a distributor set up to allocate the spark from the ignition coil timed to the correct cylinder. The coil was basically a transformer to step up the low battery voltage (6 or 12 V) to the high ignition voltage required to jump a spark plug gap. The points allow the coil magnetic field to build. When the points open by a cam arrangement, the magnetic field collapses and a large output voltage (20 kV or greater) is produced. The capacitor has two functions. Its main function is to form a series resonant circuit with the ignition coil. During resonance, energy is repeatedly transferred to the secondary side until the energy is exhausted. As a result of this resonance the duration of the spark is sustained and so implements a good flame front in the air/fuel mixture. The capacitor, by default minimizes arcing at the contacts at the point of opening. This reduces contact burning and maximizes point life. The Kettering system became the primary ignition system for many years in the automotive industry due to its lower cost, higher reliability and relative simplicity.

- Modern ignition systems
- The ignition system is typically controlled by a key operated Ignition switch.
- Mechanically timed ignition
- Distributor cap

Most four-stroke engines have used a mechanically timed electrical ignition system. The heart of the system is the distributor. The distributor contains a rotating cam driven by the engine's drive, a set of breaker points, a condenser, a rotor and a distributor cap. External to the distributor is the ignition coil, the spark plugs and wires linking the distributor to the spark plugs and ignition coil. The system is powered by a lead-acid battery, which is charged by the car's electrical system using a dynamo or alternator. The engine operates contact breaker points, which interrupt the current to an induction coil (known as the ignition coil). The ignition coil consists of two transformer windings — the primary and secondary. These windings share a common magnetic core. An alternating current in the primary induces an alternating magnetic field in the core and hence an alternating current in the secondary. The ignition coil's secondary has more turns than the primary. This is a step-up transformer, which produces a high voltage from the secondary winding. The primary winding is connected to the battery (usually through a current-limiting ballast resistor). Inside the ignition coil one end of each winding is connected together. This common point is taken to the capacitor/contact breaker junction. The other end of the secondary is connected to the rotor. The distributor cap sequences the high voltage to the respective spark plug. Ignition circuit diagram for mechanically timed ignition The ignition firing sequence begins with the points (or contact breaker) closed. A steady current flows from the battery, through the current-limiting resistor, through the primary coil, through the closed breaker points and finally back to the battery. This current produces a magnetic field within the coil's core. This magnetic field forms the energy reservoir that will be used to drive the ignition spark. As the engine turns, the cam inside the distributor rotates. The points ride on the cam so that as a piston reaches the top of the engine's compression cycle, the cam causes the breaker points to open. This breaks the primary winding's circuit and abruptly stops the current through the breaker points. Without the steady current through the points, the magnetic field generated in the coil immediately collapses. This severe rate of change of magnetic flux induces a high voltage in the coil's secondary windings. At the same time, current exits the coil's primary winding and begins to charge up the capacitor (condenser) that lies across the open breaker points. This capacitor and the coil's primary windings form an oscillating LC circuit. This LC circuit produces a damped, oscillating current which bounces energy between the capacitor's electric field and the ignition coil's magnetic field.

The oscillating current in the coil’s primary produces an oscillating magnetic field in the coil. This extends the high voltage pulse at the output of the secondary windings. This continues beyond the time of the initial field collapse pulse. The oscillation continues until the circuit’s energy is consumed. The ignition coil's high voltage output is directed to the distributor cap. A turning rotor, located on top of the breaker cam within the distributor cap, sequentially directs the output of the secondary winding to the spark plugs. The high voltage from the coil's secondary (typically 20,000 to 50,000 volts) causes a spark to form across the gap of the spark plug. This, in turn, ignites the compressed air-fuel mixture within the engine. It is the creation of this spark which consumes the energy that was stored in the ignition coil’s magnetic field. The flat twin cylinder 1948 Citroën 2CV used one double ended coil without a distributor, and just contact breakers, in a wasted spark system. Citroen 2CV wasted spark ignition system Some two-cylinder motorcycles and motor scooters had two contact points feeding twin coils each connected directly to the spark plug without a distributor; e.g. the BSA Thunderbolt and Triumph Tigress.

High performance engines with eight or more cylinders that operate at high r.p.m. (such as those used in motor racing) demand both a higher rate of spark and a higher spark energy than the simple ignition circuit can provide. This problem is overcome by using either of these adaptations: Two complete sets of coils, breakers and condensers can be provided - one set for each half of the engine, which is typically arranged in V-8 or V-12 configuration. Although the two ignition system halves are electrically independent, they typically share a single distributor which in this case contains two breakers driven by the rotating cam, and a rotor with two isolated conducting planes for the two high voltage inputs. A single breaker driven by a cam and a return spring is limited in spark rate by the onset of contact bounce or float at high rpm. This limit can be overcome by substituting for the breaker a pair of breakers that are connected electrically in series but spaced on opposite sides of the cam so they are driven out of phase. Each breaker then switches at half the rate of a single breaker and the "dwell" time for current buildup in the coil is maximized since it is shared between the breakers. The Lamborghini V-8 engine has both these adaptations and therefore uses two ignition coils and a single distributor that contains 4 contact breakers. A distributor-based system is not greatly different from a magneto system except that more separate elements are involved. There are also advantages to this arrangement. For example, the position of the contact breaker points relative to the engine angle can be changed a small amount dynamically, allowing the ignition timing to be automatically advanced with increasing revolutions per minute (RPM) or increased manifold vacuum, giving better efficiency and performance. However it is necessary to check periodically the maximum opening gap of the breaker(s), using a feeler gauge, since this mechanical adjustment affects the "dwell" time during which the coil charges, and breakers should be re-dressed or replaced when they have become pitted by electric arcing. This system was used almost universally until the late 1970s, when electronic ignition systems started to appear.

Electronic ignition

The disadvantage of the mechanical system is the use of breaker points to interrupt the low-voltage high-current through the primary winding of the coil; the points are subject to mechanical wear where they ride the cam to open and shut, as well as oxidation and burning at the contact surfaces from the constant sparking. They require regular adjustment to compensate for wear, and the opening of the contact breakers, which is responsible for spark timing, is subject to mechanical variations. In addition, the spark voltage is also dependent on contact effectiveness, and poor sparking can lead to lower engine efficiency. A mechanical contact breaker system cannot control an average ignition current of more than about 3 A while still giving a reasonable service life, and this may limit the power of the spark and ultimate engine speed. Example of a basic electronic ignition system. Electronic ignition (EI) solves these problems. In the initial systems, points were still used but they handled only a low current which was used to control the high primary current through a solid state switching system. Soon, however, even these contact breaker points were replaced by an angular sensor of some kind - either optical, where a vaned rotor breaks a light beam, or more commonly using a Hall effect sensor, which responds to a rotating magnet mounted on the distributor shaft. The sensor output is shaped and processed by suitable circuitry, then used to trigger a switching device such as a thyristor, which switches a large current through the coil.

The first electronic ignition (a cold cathode type) was tested in 1948 by Delco-Remy, while Lucas introduced a transistorized ignition in 1955, which was used on BRM and Coventry Climax Formula One engines in 1962. The aftermarket began offering EI that year, with both the AutoLite Electric Transistor 201 and Tung-Sol EI-4 (thyratron capacitive discharge) being available.[4] Pontiac became the first automaker to offer an optional EI, the breakerless magnetic pulse-triggered Delcotronic, on some 1963 models; it was also available on some Corvettes. The first commercially available all solid-state (SCR) capacitive discharge ignition was manufactured by Hyland Electronics in Canada also in 1963. Ford fitted a Lucas system on the Lotus 25s entered at Indianapolis the next year, ran a fleet test in 1964, and began offering optional EI on some models in 1965.Beginning in 1958, Earl W. Meyer at Chrysler worked on EI, continuing until 1961 and resulting in use of EI on the company's NASCAR hemis in 1963 and 1964.

II. Ignition in rockets

The ignition system in the rocket will have

1) The combustion in a solid propellant motor involves exceedingly **complex reactions** taking place in the solid, liquid, and gas phases of a heterogeneous mixture.

2) Motor **ignition** must usually be **complete in a fraction of a second** for all but the very large motors The motor pressure rises to an equilibrium state in a very short time.

3) Solid propellant ignition consists of a **series of complex rapid events**

4) The **igniter** in a solid rocket motor generates **the heat and gas** required for motor ignition.

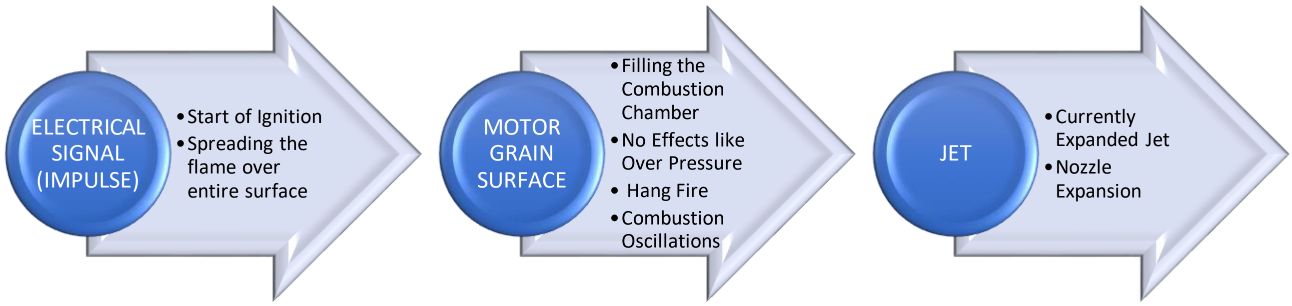

Fig-1: The process of ignition in rocket

III. Types of Solid Propellant Igniters

Igniters are devices or assemblies that produce a specific level of heat in order to initiate a larger combustion reaction. They are produced in simple and complex designs according to application use. Types of igniters are **pyrotechnic**, **nozzle cap, hot surface** and **spark** (or **electrode**) devices.

1. Pyrotechnic Igniters

- Pyrotechnic igniters are defined as igniters using pyrotechnic composition or energetic propellant like chemical formulations. Pyrotechnic igniters are frequently controlled electrically.
- They are initiated to ignite materials.
- **Thermites** are a pyrotechnic mixture of metal powder and oxide, which generates a reaction called a thermite response. While this reaction is not typically explosive, it can produce rapid bursts of high temperatures under the right conditions. This reaction's higher temperatures are generally concentrated on a very small area for a short period of time.

Additional Considerations

- These devices may require maintenance to adhere to safety standards, which should be verified through the manufacturer.

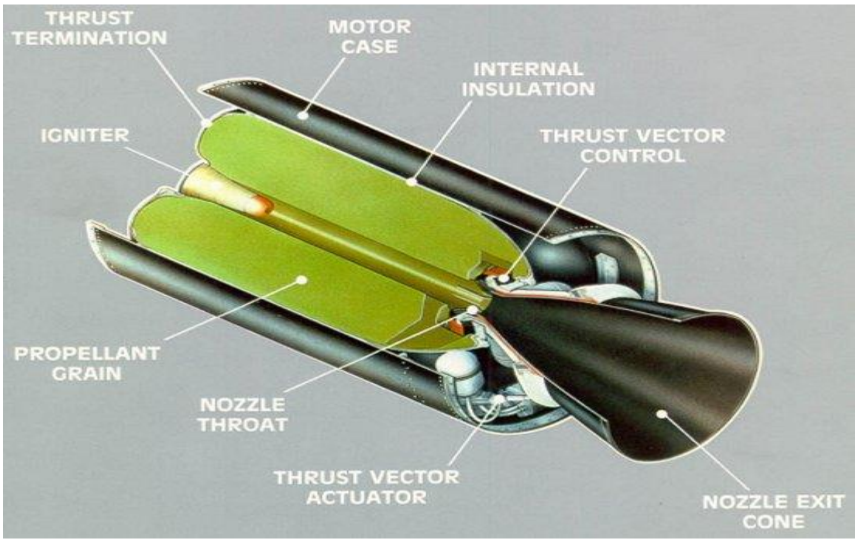

Fig-2: The pyrotechnic igniter

2. Nozzle Cap Based Igniter

Nozzle cap-based igniters are very useful in complicated rocket motors where igniters can not be mounted at any other location. As it is at the nozzle end, propellant loading at the head

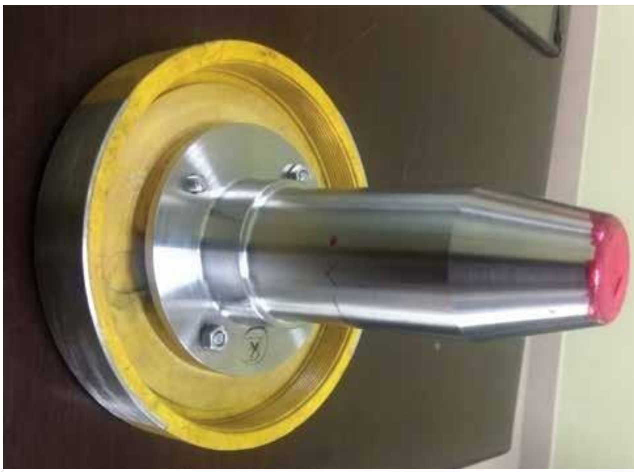

Fig-2: The nozzle cap igniter

3. Hot Surface Igniters or Ceramic Igniters

Invented in 1969, these igniters are composed of advanced **ceramic materials**. These devices are also the most commonly used electronic ignition systems today. They are generally employed for applications such as **space furnaces** and **heaters**. Hot surface igniters are commonly used for their reliability and durability potential.

Hot Surface Igniter Configuration
The two composition materials generally associated with hot surface igniters are **silicon carbide** and **silicon nitride**.

- **Silicon carbide** is a compound of carbon and silicon and is characterized by a low density and oxidation resistance. This compound, seen in igniters, has good high temperature strength.
- **Silicon nitride** is a chemical compound of silicon and nitrogen. It is a hard ceramic with a high strength and is durable over a broad temperature range. Its notable characteristics include durability over a high temperature range.

Fig-3: The hot surface igniter

Additional Considerations

- Because these igniters are made of ceramics, they are considered durable and thermally robust and may last from 3-5 years.

- It gradually weaken over time and use and will eventually generate less heat than their full potential; they should be replaced when this occurs. Hot surface igniters may also experience premature burnout.

4. Spark Igniters

Spark igniters are also known as flame igniters, according to their application. They are **electric** and no gas leaks are involved. Spark igniters function as a device that ignites compressed fuels, such as aerosol gas, petroleum gas that is generally liquefied, and ethanol. Some manufacturers produce spark igniters (also called spark **plugs**) that produce an ultra thrust ignition, which provides reduced emissions and a faster start.

A spark plug may be considered either **hot** or **cold**. The difference is hot spark plugs generally hold more heat in the physical tip of the spark plug, while cold generate more heat out of the tip and lower its temperature.

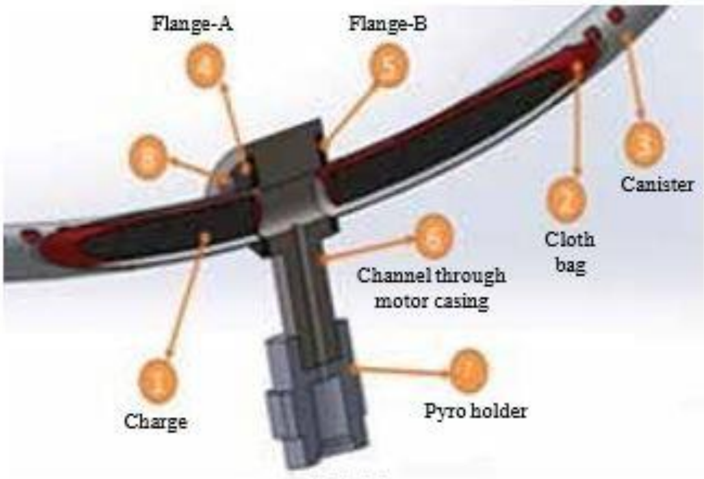

Fig-4: Spark igniter

Spark Igniter Configuration

- Spark igniters are capable of igniting more than one burner at a time, and they can be controlled by an on and off switch. The spark is produced at a set of make and break contacts.
- These are made of **tungsten** for extended durability. **Tungsten** is a steel gray metal that is distinguished by its robust physical properties. It has the highest melting point of all metals it its pure form,

Additional Considerations

- A certain energy level must be maintained or the spark will dissipate.
- Manufacturers of these igniters suggest inspecting coloring of the tip (which should appear light brown) of the igniter block to ensure proper function.

IV. Types of Liquid Propellant Igniters

Hypergolic Ignition

- Hypergolic igniters use a combination of hypergolic reactants (hypergols) which ignite spontaneously upon contact.
- In hypergolically ignited motors, initiation of combustion may occur simultaneous with or just prior to main propellant ignition.
- Common hypergolic propellant combinations include monomethyl hydrazine, hydrazine, and unsymetric dimethlhydrazine paired with Nitrogen Tetroxide or Nitric Acid.
- Example : The Rocketdyne F1 used on the Saturn V vehicle as well as the SpaceX Merlin engine

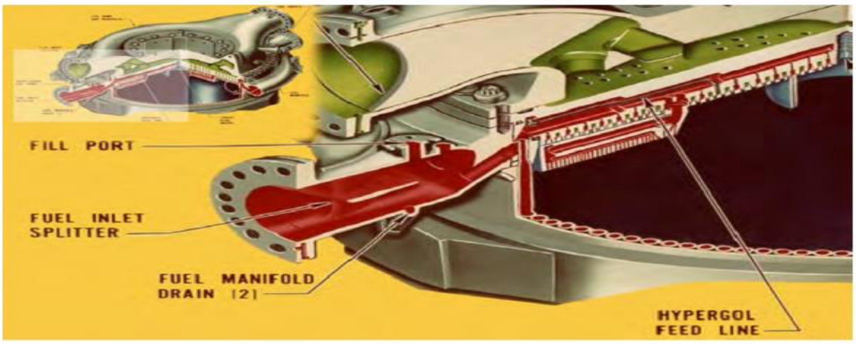

Fig-5: Hypergolic igniter

Augmented Spark Ignition

- Augmented spark ignition, systems such as that shown in Figure are essentially liquid bi-propellant engines with flow rates low enough to allow for direct spark initiation within a separate small igniter combustion chamber.
- Combustion of the igniter reactants then builds the necessary power release level to ensure reliable and timely ignition of the main propellant. Precedent exists for using high voltage electrostatic arc type ignition sources to the light the main engine propellants

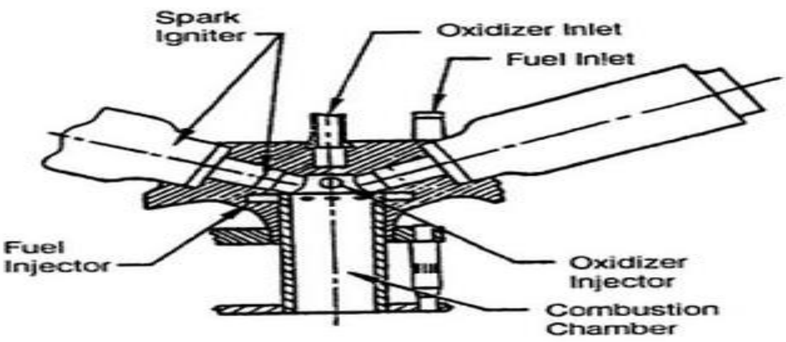

Fig-5: Augmented Spark igniter

Igniter Design Consideration

The ignition will be successful once enough grain surface is ignited and should be burning, The motor will continue to raise its own pressure to the operating chamber pressure. The critical process seems to be a gas-phase reaction above the burning surface, when propellant vapours or decomposition products interact with each other and with the igniter gas products. If the igniter is not powerful enough, some grain surfaces may burn for a short time, The flame will be extinguished.

Combustion Chamber Design

Spherical chambers give the least internal surface area and mass per unit chamber volume; they are expensive to build and several have been tried. Today we prefer a cylindrical chamber (or slightly tapered cone frustum) with a flat injector and a converging-diverging nozzle The volume has to be large enough for adequate mixing, evaporation, and complete combustion of propellants. Chamber volumes vary for different propellants with the time delay necessary to vaporize and activate the propellants and with the speed of reaction of the propellant combination. When the chamber volume is too small, combustion is incomplete and the performance is poor. The chamber diameter and volume can influence the cooling requirements. If the chamber volume and the chamber diameter are large, the heat transfer rates to the walls will be reduced, the area exposed to heat will be large, and the walls are somewhat thicker. There is an optimum chamber volume and diameter where the total heat absorbed by the walls will be a minimum. Manufacturing considerations favour a simple chamber geometry, such as a cylinder with a double cone bow-tie-shaped nozzle. In some applications the length of the chamber and the nozzle relate directly to the overall length of the vehicle. A large-diameter but short chamber can allow a somewhat shorter vehicle with a lower structural inert vehicle mass. Low cost materials, and simple fabrication processes. The gas pressure drop for accelerating the combustion products within the chamber should be a minimum; any pressure reduction at the nozzle inlet reduces the exhaust velocity

V. Fuel Injectors for rockets

The functions of the injector are similar to those of a carburetor of an internal combustion engine. The injector has to introduce and meter the flow of liquid propellants to the combustion chamber, cause the liquids to be broken up into small droplets (a process called atomization). Distribute and mix the propellants in such a manner that a correctly proportioned mixture of fuel and oxidizer will result, with uniform propellant mass flow and composition over the chamber cross section.

Single or Self Impingement

The injection hole pattern on the face of the injector is closely related to the internal manifolds or feed passages within the injector. These provide for the distribution of the propellant from the injector inlet to all the injection holes.

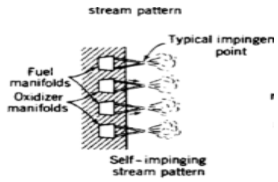

Fig-6: Single or Self Impingement

Double or Duel Impingement

The two liquid streams then form a region which breaks up into droplets.

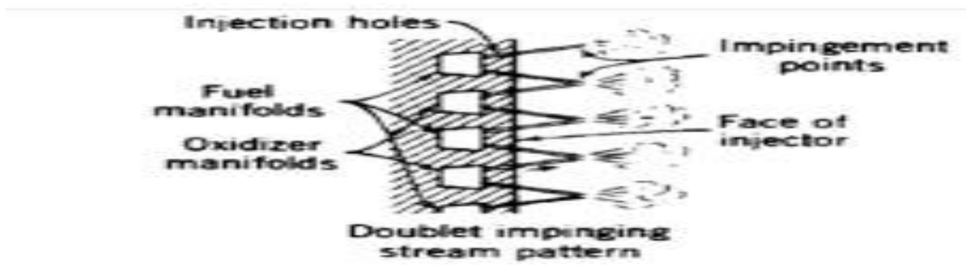

Fig-7: Double or Duel Impingement

Triple Impingement

The three liquid streams then form a region which breaks up into droplets

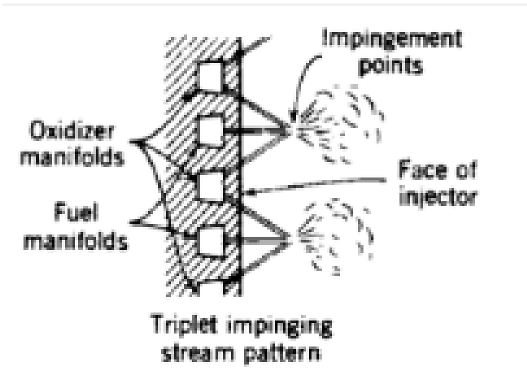

Fig-8: Triple Impingement

Non -Impingement or Shower Head type

The non-impinging or shower head injector employs non impinging streams of propellant usually emerging normal to the face of the injector. It relies on turbulence and diffusion to achieve mixing. The German World War II V-2 rocket used this type of injector. This type is now not used, because it requires a large chamber volume for good combustion

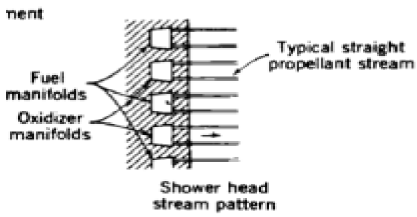

Fig-9: Non -Impingement type

Swirl type Injectors

The circumferential velocity component is first generated as the propellant enters through helical or tangential inlets producing a thin, swirling liquid sheet. A gas-filled hollow core is then formed along the centreline inside the injector due to centrifugal force of the liquid sheet. Because of the presence of the gas core, the discharge coefficient is generally low

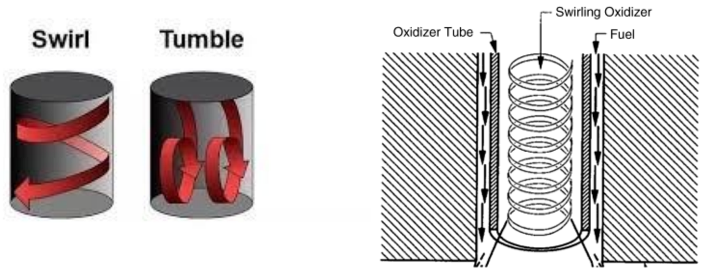

Fig-10: Swirl type

VI. Propellant Tank

In liquid bipropellant rocket engine systems propellants are stored in one or more oxidizer tanks and one or more fuel tanks. In monopropellant rocket engine systems have, of course, only one set of propellant tanks. There are also one or more high-pressure gas tanks, the gas being used to pressurize the propellant tanks. Tanks can be arranged in a variety of ways, and the tank design can be used to exercise some control over the change in the location of the vehicle's center of gravity.

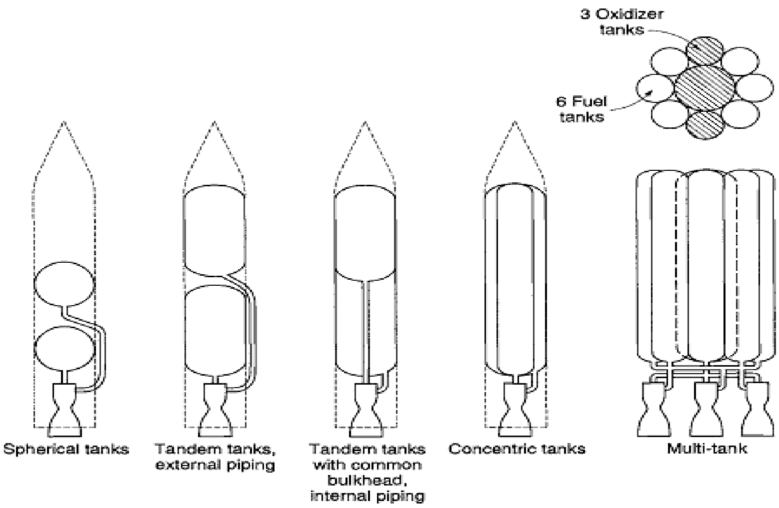

Fig-11: Propellant tank types

Propellant Slosh

Propellant slosh refers to the movement of liquid inside another moving object or liquid.“Inertial waves" and can be an important effect in spinning spacecraft dynamics. Liquid slosh inmicrogravity is relevant to spacecraft, most commonly Earth-orbiting satellites, and must take account of liquid surface tension which can alter the shape of the liquid slug.Propellant slosh can introduce uncertainty in spacecraft attitude which is often called jitter. Similar phenomena can cause pogo oscillation and can result in structural failure of space vehicle.

SLOSHSAT-FLEVO (Sloshsat Facility for Liquid Experimentation and Verification in Orbit) is a microsatellite launched to investigate the dynamics of fluids in microgravity

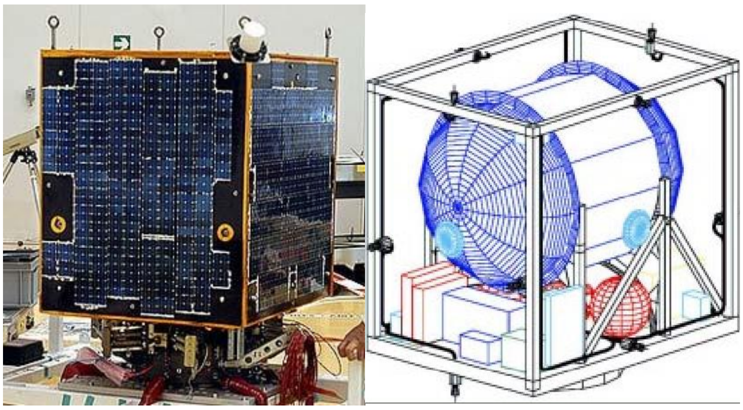

Fig-11: SLOSHSAT-FLEVO

Multiple sensors were used to monitor the behavior of water in an instrumented tank and how sloshing affects the attitude control of launchers and space vehicles.The project is a joint program between ESA, the Netherlands Agency for Aerospace Programmes, and the Israel Space Agency.Launched on 12 February 2005

Propellant Hammering for rockets

“Hydraulic Shock” is a pressure surge or shockwave resulting when a fluid (usually a liquid but sometimes also a gas) in motion is forced to stop or change direction suddenly (momentum change).

The reversed momentum then continues to multiply the further it travels before being stopped. This pressure wave can cause major problems, from noise and vibration to pipe rupture or collapse. It is possible to reduce the effects of the water hammer pulses with accumulators, expansion tanks, surge tanks, blowoff valves, and other features.The effects can be avoided by ensuring that no valves will close too quickly arranged with significant flow.

Fig-12: Hammering

Geysering

"Geysering" is applied to the specific phenomenon that occurs in a liquid system when a column of liquid in long vertical lines is expelled by the release of vapour at a rate in excess of that rate which may occur as a normal function of bubble release.

Several approaches were conceived as possibilities to reduce and/or eliminate geysering. These included:

1) Insulation
2) Refrigeration
3) Inert gas in-jection (helium)
4) External recirculation lines
5) Internal recirculation lines
6) Cross-feed recirculation lines
7) Check valve (shock elimination);
8) Sub-cooled topping; and
9) Line surface treatment.

VII. COMBUSTION INSTABILITY

A solid propellant rocket is formed by four main components. A case containing the solid propellant and withstanding internal pressure when the rocket is operating. The solid propellant charge (or grain), which is usually bonded to the inner wall of the case and occupies before ignition the greater part of its volume. When burning, the solid propellant is transformed into hot combustion products. The volume occupied by the combustion products is called combustion chamber. The nozzle channels the discharge of the combustion products and because of its shape accelerates them to supersonic velocity. The igniter, which can be a pyrotechnic device or a small rocket, starts the rocket operating when an electrical signal is received.

Two main categories of propellant grains

Double Base: A homogeneous propellant grain, usually nitrocellulose dissolved in nitroglycerin. Both ingredients are explosive and act as a combined fuel, oxidizer and binder

Composite: A heterogeneous propellant grain with oxidizer crystals and powdered fuel held together in a matrix of synthetic rubber binder.Less hazardous to manufacture and handle

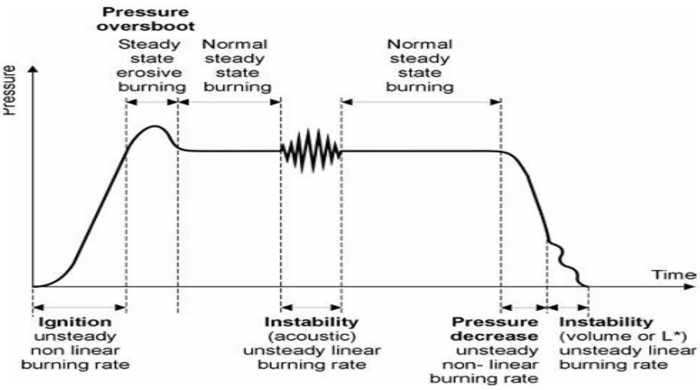

Fig-13: Combustion Instabilty

The critical technologies concern the propellant itself, the propellant grain design, the thermal insulation, the nozzle design and the case. Besides, another well known difficulty is related to the near impossibility to perform detailed measurement inside the combustion chamber, due to the severe conditions prevailing there

Burning Rate

Propellant burning rate plays a central role in motor operation. That is why perfect control of burning rate is absolutely mandatory.

Steady State Regimes

Normal (regular) regime: burning rate is depending on only two parameters: pressure and initial temperature. It is known that burning rate can change with the propellant temperature. Since only a very thin layer of the propellant is usually affected by the chemical transformation during the combustion process, a good assumption is that the initial grain temperature (considered as uniform) is an external parameter, without variation during operation

Erosive burning regime:

If the flow above the combustion surface is fast, it is possible to observe an increase in the burning rate for a given pressure (and, less frequently, a decrease in the burning rate for some double base propellants).The convective thermal flux to the combustion surface due to the interaction between flow turbulence and flames.In this condition, burning rate is no longer pure feature of the propellant but a property mixing propellant and flow. Erosive burning can be responsible of a pressure overshoot at ignition.

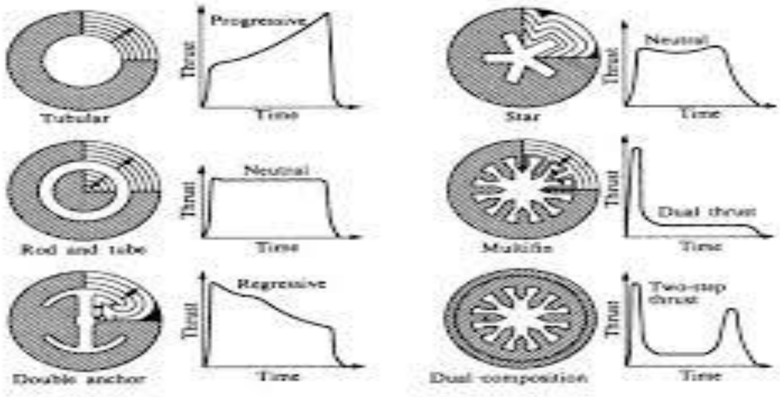

Fig-14: Grain Configuration

Unsteady Regimes

When pressure or more generally the conditions above the combustion surface are changing very rapidly, direct dependence of burning rate on instantaneous parameters is no longer right; time is also involved. Several situations bring into play unsteady burning rate, essentially the transient phases (ignition and operation end) and the instability. The common approach is to make the distinction between linear burning rate and non-linear burning rate. Linear burning rate corresponds to small perturbations of all the parameters around a steady state and it is typically the case for the low level instability.

SCHOOL OF MECHANICAL ENGINEERING

DEPARTMENT OF AERONAUTICAL ENGINEERING

UNIT – II - AERODYNAMICS OF ROCKETS -SAE1402

I. Airframe Components of the Rocket

The structural system, or frame, is similar to the fuselage of an airplane. The frame is made from very strong but light weight materials, like titanium or aluminium, and usually employs long "stringers" which run from the top to the bottom which are connected to "hoops" which run around the circumference. The "skin" is then attached to the stringers and hoops to form the basic shape of the rocket. The skin may be coated with a thermal protection system to keep out the heat of air friction during flight and to keep in the cold temperatures needed for certain fuels and oxidizers. Fins are attached to some rockets at the bottom of the frame to provide stability during the flight.

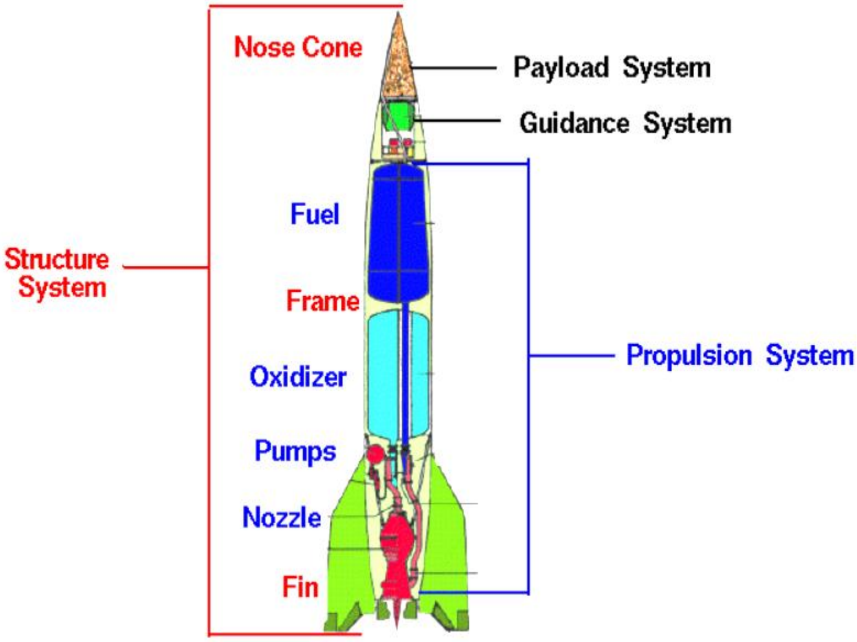

Fig 1: Airframe components of the Rocket

The payload system of a rocket depends on the rocket's mission. The earliest payloads on rockets were fireworks for celebrating holidays. The payload of the German V2, shown in the figure, was several thousand pounds of explosives. Following World War II, many countries developed guided ballistic missiles armed with nuclear warheads for payloads. The same rockets were modified to launch satellites with a wide range of missions; communications, weather monitoring, spying, planetary exploration, and observatories, like the Hubble Space Telescope. Special rockets were developed to launch people into earth orbit and onto the surface of the Moon.

The guidance system of a rocket may include very sophisticated sensors, on-board computers, radars, and communication equipment to manoeuvre the rocket in flight. Many different methods have been developed to control rockets in flight. The V2 guidance system included small vanes in the exhaust of the nozzle to deflect the thrust from the engine. Modern rockets typically rotate the nozzle to manoeuvre the rocket. The guidance system must also provide some level of stability so that the rocket does not tumble in flight.

II. Forces Acting on the Rocket

The forces acting on a rocket are the thrust, the aerodynamic forces, the gravitational attractions, the wind and solar radiation pressure. The two last forces are usually small and are therefore neglected. In this study, the rocket trajectory is considered two dimensional. This assumption has been made because the tool developed to simulate the rocket trajectory has to be relatively simple and fast. Also this tool is used for making preliminary estimates and so a two dimensional problem is enough for this study. Thus, the trajectory is two dimensional and is contained in a fixed plane. The body-fixed coordinate system is the frame of reference of the rocket. The x-axis corresponds to the longitudinal axis of the rocket, the y-axis is perpendicular to the x-axis in the lateral plane.

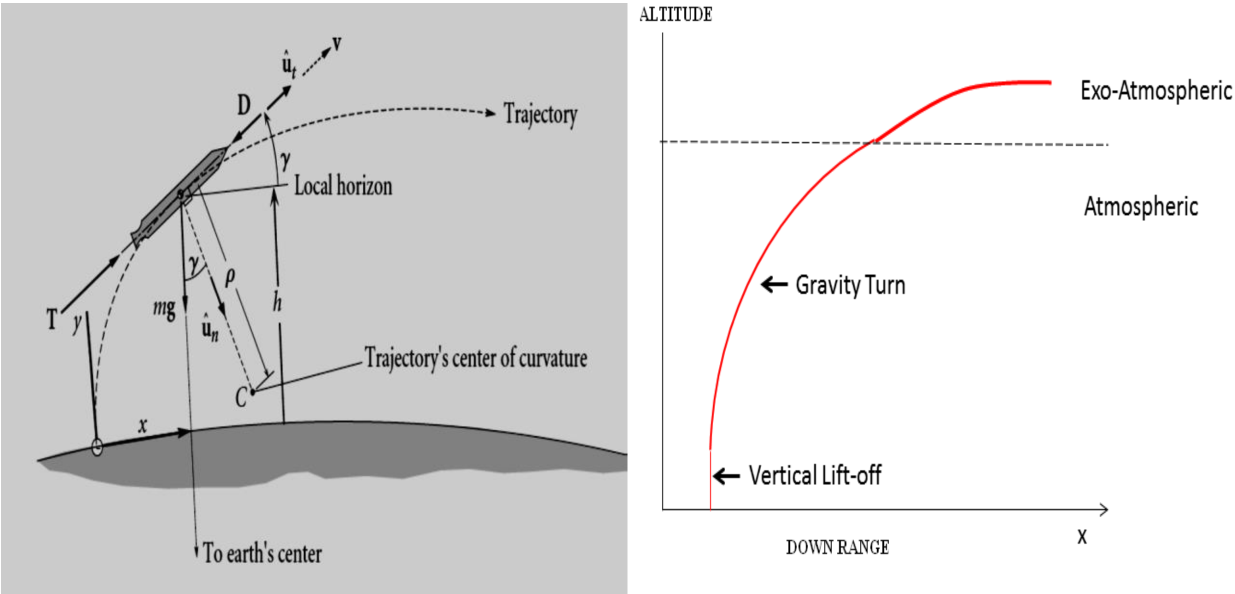

Fig 2: Various phases of the Rocket

Ascent Phase

A typical launcher starts its mission locked to the Launch pad. The engines are not yet ignited, or the thrust provided is still lower than the vehicle weight. For solid propulsion, the time between ignition and lift off is extremely short (less than 1 s). In the case of liquid propulsion, this time may be longer, allowing the verification of the correct engine operations, before releasing the vehicle.The first phase is a vertical lift off, required to gain velocity before the gravity turn phase and avoid any contact with the launch pad tower like 170-200 meters. The duration of the ascent phase varies from vehicle to vehicle and the current tendencies is to decrease it, because of the developments made in technology. The necessary initial conditions include the flight path angle equal to 90(89.5 deg) and velocity zero.

Gravity Turn

A launch vehicle typically starts its ascent with a vertical rise and in order to reach a horizontal position at burnout, the vehicle has to turn and this is automatically done by dynamics, in what is termed a gravity turn trajectory, or the pitch over maneuver**.**After the vertical rise, the vehicle is nudged during a certain amount of time in order to reach a horizontal position at burnout. The pitch over maneuver has to be executed in order to minimize the gravity losses, as during the **vertical ascension the gravity directly acts** against the thrust of the rocket, and also the pitch over should be applied when the vertical velocity is small in order to reduce the aerodynamic losses during the maneuver

T	=	Thrust of launch vehicle	[N]
D	=	Drag of the launch vehicle	[N]
g	=	Acceleration due to gravity	[m/s^2]
L	=	Lift of the launch vehicle	[N]
m	=	Mass of the vehicle	[kg]
α	=	Angle of attack	[deg]

The angle between the Velocity vector (Direction of flight) and Thrust Direction

θ	=	Pitch angle	[deg]

The angle between the Horizontal reference (local horizon) and Thrust direction

γ	=	Fight path angle	[deg]

The angle between the Horizontal reference (local horizon) and Velocity vector.

i.e. the sum of angle of attack and pitch angle.

$$\gamma = \alpha + \theta$$

The Newton's equation of motion considered are

$$\boldsymbol{ma_x = -D\cos\alpha - L\sin\alpha + T\cos\alpha - mg\sin\theta}$$

$$\boldsymbol{ma_y = -D\sin\alpha + L\cos\alpha - T\sin\alpha - mg\cos\theta}$$

where

a_x	=	Acceleration projected on the rocket's longitudinal axis	[m/s^2]
a_y	=	Acceleration projected on the rocket's lateral axis	[m/s^2]

Assumptions

1) Angle of attack is smaller & equal to zero and so the Lift becomes equal to zero.
2) The flight path angle is now the pitch angle.
3) Thrust aligned with velocity vector ($\alpha = 0$)

Finally, the system of equations now becomes,

$$\frac{dx}{dt} = v\cos\gamma$$

$$\frac{dh}{dt} = v\sin\gamma$$

$$\frac{dV}{dt} = \frac{(T-D)}{m} - g\sin\gamma$$

$$V\frac{d\gamma}{dt} = -g\cos\gamma + \frac{v^2}{r_0 + h}\cos\gamma$$

where

r_0	=	radius of the earth	[m]
h	=	Altitude	[m]
x	=	Ground range	[m]
V	=	Launch vehicle velocity	[m/s]

Free Flight Phase

As the vehicle emerges from **the atmosphere a better trajectory than the gravity turn can be used**. It has a (present) position and velocity, and it is desired to achieve a different position and velocity at thrust termination. The only two forces that can cause the vehicle to accomplish the desired position and velocity changes are thrust and gravity.

Coast Phase

The coast phases are performed between **the jettison of a stage and the ignition of the next one.** So the propagation of the trajectory is only influenced by the gravitational force, in real cases aerodynamic forces need to be considered, but in this case as we know there is **no angle of attack during atmospheric flight** so they can be disregarded. The coast phases are often used for injection into GTO and for interplanetary trajectories, where the constant thrust can't be applied.

III. Rocket's Stability

During the flight of rocket, gusts of wind or thrust instabilities, can cause the rocket to "wobble", or change its attitude in flight. Poorly built or designed rockets can also become unstable in flight. This lesson is about what makes a rocket unstable in flight and what can be done to improve its stability. A rocket in flight can move two ways; it can **translate**, or change its location from one point to another, and it can **rotate**, meaning that it can roll around on its axis.

Roll

Most rockets are symmetric about a line from the tip of the nose to the center of the nozzle exit. We will call this line the **roll axis** and motion about this axis is called a **rolling motion**.The **center of gravity** lies along the roll axis.

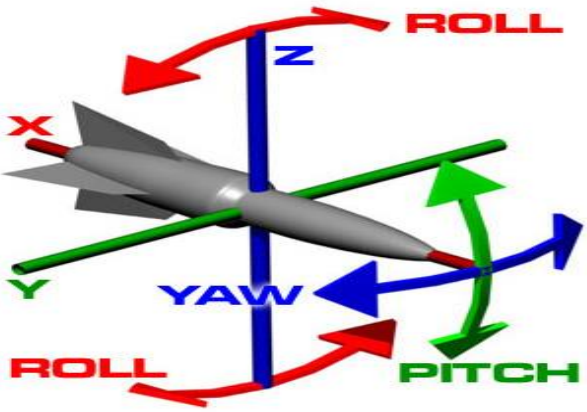

Fig 2: Roll, Yaw & Pitch

Yaw and Pitch

When a rocket wobbles from side to side, this movement is called a yaw motion. A pitch motion is an up or down movement of the nose of the rocket**.**

Center of Gravity – CG

As a rocket flies through the air, it both translates and rotates. The rotation occurs about a point called the center of gravity, which is the average location of the weight of the rocket.

Fig 3: CG of Rocket

Center of Pressure – CP

The average location of the pressure on the rocket is called the center of pressure. The parts of the rocket that influences the location of the center of pressure the most are the fins.

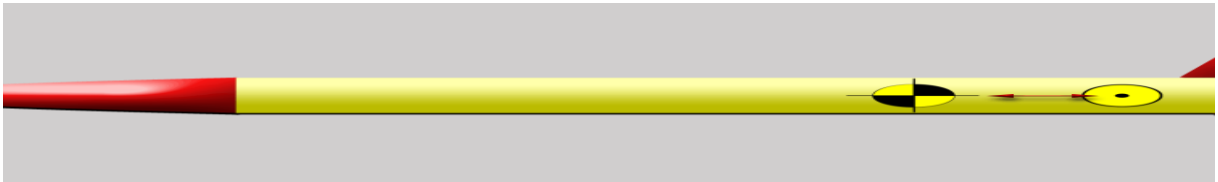

Fig 4: CP of Rocket

If the **center of gravity is in front of the center of pressure**, the rocket will return to its initial flight conditions if it is disturbed. This is called a **restoring force** because the forces "restore" the rocket to its initial condition and the rocket is said to be **stable**

If the center of gravity and the center of pressure are in the same location, it is called **neutral stability**.A rocket with **neutral stability** may make a stable or unstable flight depending on the forces acting on it.

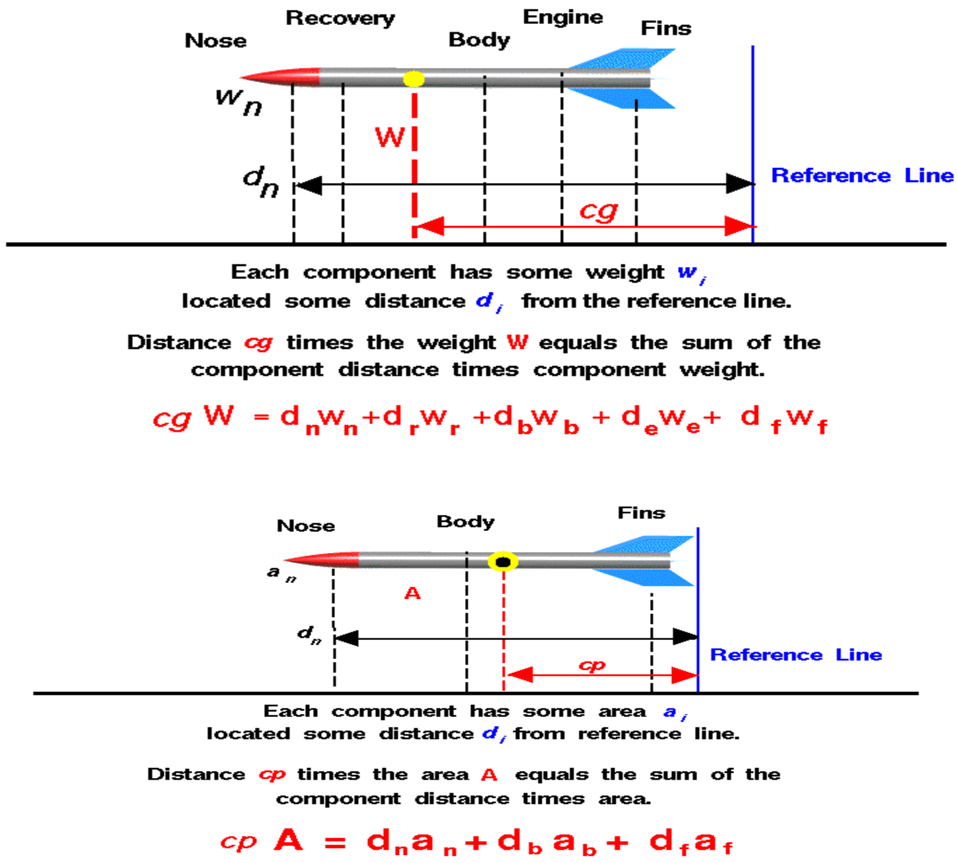

Fig 5: Calculation of CG and CP

If the **center of pressure is behind the center of gravity**, the lift and drag forces maintain their directions but the direction of the torque generated by the forces is reversed. This is called a **de-stabilizing force**. Any small displacement of the nose generates forces that cause the displacement to increase. Such a flight condition is **unstable**

Correcting Unstable Flight

To move the Center of Gravity:

- Add or remove weight in the nose cone.
- Redistribute the Payload
- Increase or decrease airframe length.

To move the Center of Pressure:

- Increase or reduce the fin size.

- Change the shape of the fins.
- Change the location of the fins.
- Increase or decrease airframe length/diameter.

One Caliber Stability

The best separation between the center of gravity is for the CP to be at least one body tube diameter in front of the CG. This is called one caliber stability.

Atmospheric Drag

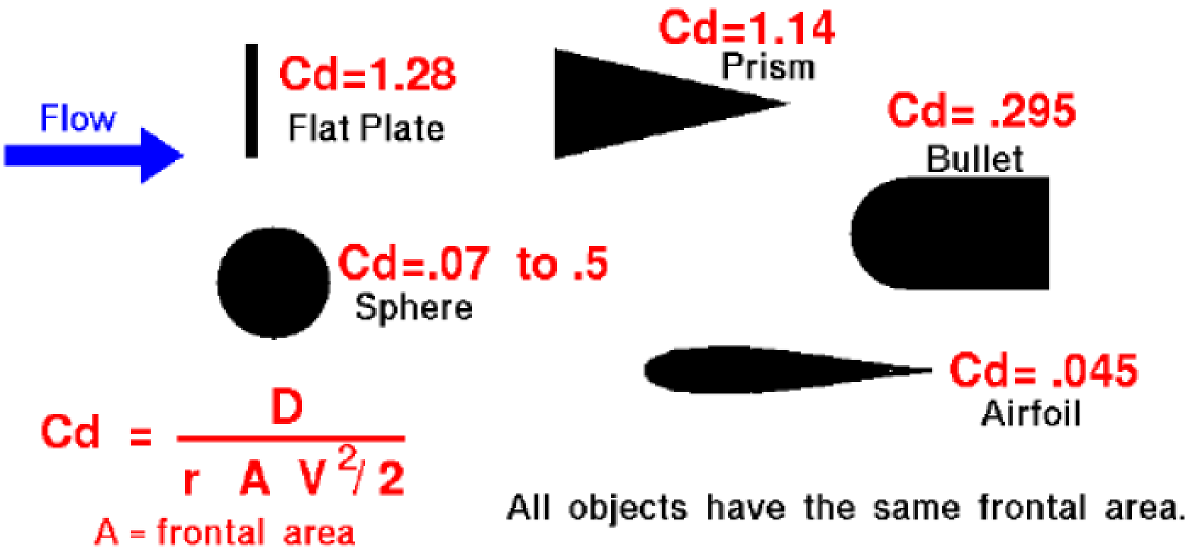

Fig 6: Calculation of CD

C_D : Drag coefficient. Contains all complex dependencies like air compressibility, viscosity body shape and angle-of-attack.

A : Reference area, typically the base diameter of the nose. Different A, affect the value of C_D.
ɖ) : Density of the atmosphere of consideration (typically 1.23kg/m^3 for air at sea-level).

v : Rocket speed

IV. MONTE CARLO SIMULATION

Monte Carlo methods are a widely used class of computational algorithms for simulating the behavior of various physical and mathematical systems, and for other computations.Monte Carlo algorithm is often a numerical Monte Carlo method used to find solutions to mathematical problems (which may have many variables) that cannot easily be solved, (e.g. integral calculus, or other numerical methods).

A Monte Carlo simulation is a statistical simulation technique that provides approximate solutions to problems expressed mathematically. It utilizes a sequence of random numbers to perform the simulation.This technique can be used in different domains: complex integral computations, economics, making decisions in specific complex problems.

In general, Monte Carlo Simulation is roughly composed of **five steps:**

1. Set up probability distributions: what is the probability distribution that will be considered in the simulation
2. Build cumulative probability distributions
3. Establish an interval of random numbers for each variable
4. Generate random numbers: only accept numbers that satisfies a given condition.
5. Simulate trials

The uncontrolled trajectory which is from the missile ejected from the launcher to the missile received the control instruction is defined as initial ballistic trajectory. Normally, the tactical missile does not begin the navigated flight instantly after ejection. Because the tactical missile is mainly depended on aerodynamics to achieve maneuverability, it needs time to get the essential flight speed. On other words, the missile is not controlled during the time from its ejection to the manoeuvrable flight. Commonly, the "starting control points" is defined as the ballistic trajectory points when the missile begins to be controlled by the guidance system.

Initial disturbance is introduced because:

(l)During missile ejection, the launch tube vibrate because of wake flow;

(2) There are many manufacturing errors during the production process of missiles. These disturbed factors could make initial conditions appear randomly distributed when the missile ejects from the tube. On pitch plane, trajectory angle and missile angular rate coz0 in body coordinate system are only needed to be considered.

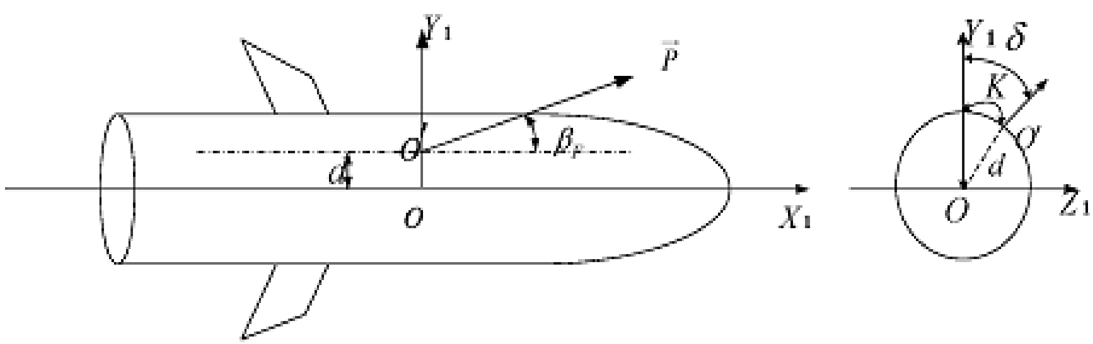

Fig 7: Mis alignment of Thrust

$$\theta_0 = \theta_0{}' + \Delta\theta_0$$

$$\omega_{z0} = \omega_{z0}{}' + \Delta\omega_{z0}$$

d : Eccentricity of thrust

β_F : Eccentric angle of thrust

δ : Initial azimuth of eccentricity of thrust(calculated from axis y_1, and clockwise rotation defined as positive)

K : Angle from oo' to axis y_1

$\vec{P}$: Thrust vector

$\overline{M_P}$: Thrust decentration moments acting on missile

Eccentricity of thrust (d) horizontal projection decomposed in body coordinate system:

$$\begin{bmatrix} d_{x1} \\ d_{y1} \\ d_{z1} \end{bmatrix} = \begin{bmatrix} 0 \\ d\cos k \\ d\sin k \end{bmatrix} \tag{3}$$

Thrust vector ($\vec{P}$) horizontal projection decomposed in body coordinate system:

$$\begin{bmatrix} P_{x1} \\ P_{y1} \\ P_{z1} \end{bmatrix} = \begin{bmatrix} P\cos\beta_F \\ P\sin\beta_F\cos\delta \\ P\sin\beta_F\sin\delta \end{bmatrix} \tag{4}$$

Thrust decentration moments ($\overline{M_P}$)horizontal projection decomposed in body coordinate system:

$$\begin{bmatrix} M_{P_{x1}} \\ M_{P_{Y1}} \\ M_{P_{Z1}} \end{bmatrix} = \begin{bmatrix} 0 & -d_{z1} & d_{y1} \\ d_{z1} & 0 & -d_{x1} \\ -d_{y1} & d_{x1} & 0 \end{bmatrix} \cdot \begin{bmatrix} P_{x1} \\ P_{y1} \\ P_{z1} \end{bmatrix}$$
$$= \begin{bmatrix} -Pd\sin k\cdot\sin\beta_F\cdot\cos\delta + \\ pd\cos k\cdot\sin\beta_F\cdot\sin\delta \\ Pd\sin k\cdot\cos\beta_F \\ -pd\cos k\cdot\cos\beta_F \\ \end{bmatrix} \tag{5}$$

V. MULTI STAGING ROCKET

A multistage (or multi-stage) rocket is a rocket that uses two or more stages, each of which contains its own engines and propellant.A tandem or serial stage is mounted on top of another stage; a parallel stage is attached alongside another stage.

Reasons For Multistaging

1. To improve performance by eliminating dead weight during powered flight.
2. To maintain acceleration within reasonable limits by reducing thrust in mid flight

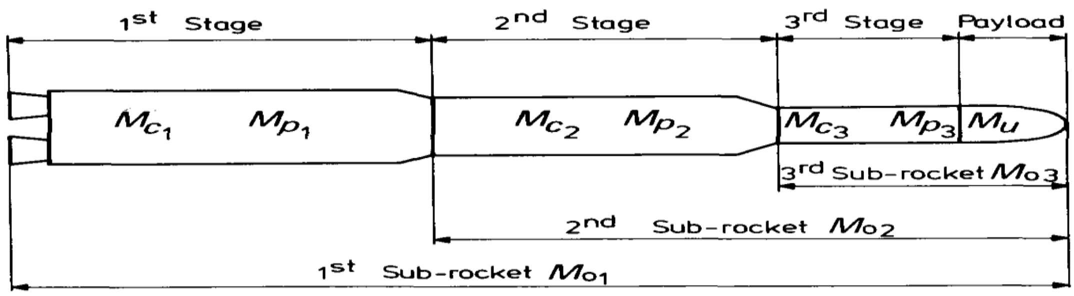

Fig 8:Sub Rocket and Staging

Stage

A stage (which is also known as a step), is a complete propulsion unit with motor, propellant feed system, tanks, propellant together with control equipment, which is discarded completely when all the propellant of that stage is consumed.

Sub Rocket

A sub rocket is a complete rocket vehicle, consisting of one or more stages together with a payload and the guidance and control system

In multistage launch vehicles the stage separation processis broadly classified into two categories. They are

1. Separation Occuring Within Atmosphere.

   Separation within the atmosphere is otherwise known as booster separation/lower stage separation/strap on separation. Firing Technique- Long Duration And Liquid Propellant Rocket

2. Separation Occuring Out Of Atmosphere.

   Ullage Rocket Technique-Short Duration Solid Propellant Rocket Motor Placed Between The Stages To Push The Lower Stage.

SCHOOL OF MECHANICAL ENGINEERING

DEPARTMENT OF AERONAUTICAL ENGINEERING

UNIT – III - BASIC CONCEPTS – SAE1402

I. The Universe

According to our present view, 10 to 20 billion years ago there was nothing but an exploding, enormously hot and dense Primeval Fireball that contained all the matter and energy of the present universe. The mean mass density is extremely low, corresponding to that of a few hydrogen atoms per ten cubic meters. The matter in the universe is mainly concentrated in objects with extremely large dimensions and of complex structure: the galaxies. Billions of these galaxies are assumed to be present in the universe. The mean distance between them is of the order of 1018 to 1020 km. Light year is used as the unit of length to express those large distances. The light year is defined as the distance traversed by light in vacuum during one year, which corresponds to about 9.46 x 1012 km. The Sun belongs to one of the galaxies, named the Milky Way. This Milky Way, which comprises about 100 billion stars, has the appearance of a large, relatively flat structure with spiral arms and a diameter of about 100,000 light years. Our Sun is located at a distance of about 30,000 light years from the center of this galaxy and is moving with a velocity of roughly 250 km/s about this center, completing one revolution in about 250 million years. The galaxy nearest to the Milky Way is the Great Magellanic Cloud at a distance of about 160,000 light years from the Sun.

Solar System

. Our Solar System consists of a central star (the Sun), the nine planets orbiting the sun, moons, asteroids, comets, meteors, interplanetary gas, dust, and all the "space" in between them. The nine planets of the Solar System are named for Greek and Roman Gods and Goddesses. The volume of space very close to the Sun, up to a distance of about 1 light year, is called the solar system. Of those objects that orbit the Sun directly or indirectly, are the planets, moons, with the remainder being significantly small Solar System bodies such as comets and asteroids.
Inner Planets: Mercury, Venus ,Earth ,Mars.
Outer Planets : Jupiter,Saturn ,Uranus,Neptune and Pluto.

The Sun

The sun's energy comes from nuclear fusion (where hydrogen is converted to helium) within its core. This energy is released from the sun in the form of heat and light. Stars produce light. Planets reflect light. A star's temperature determines its "color." The coldest stars are red. The hottest stars are blue.

The Planets

Planets are categorized according to composition and size. There are two main categories of planets: small rocky planets (Mercury, Venus, Earth, Mars, and Pluto) and gas giants (Jupiter, Saturn, Uranus, and Neptune). The Characteristics of Small Rocky Planets are they are made up mostly of rock and metal. They are very heavy. They move slowly in space. They have no rings and few moons (if any). They have a diameter of less than 13,000 km. The Characteristics of Gas Giants are they are made up mostly of gases (primarily hydrogen & helium). They are very light for their size. They move quickly in space. They have rings and many moons. They have a diameter of less than 48,000 km

Mercury

Mercury has a revolution period of 88 days. Mercury has extreme temperature fluctuations, ranging from 800 F (daytime) to -270F (nighttime). Even though it is the closest planet to the sun, Scientists believe there is ICE on Mercury! The ice is protected from the sun's heat by crater shadows.

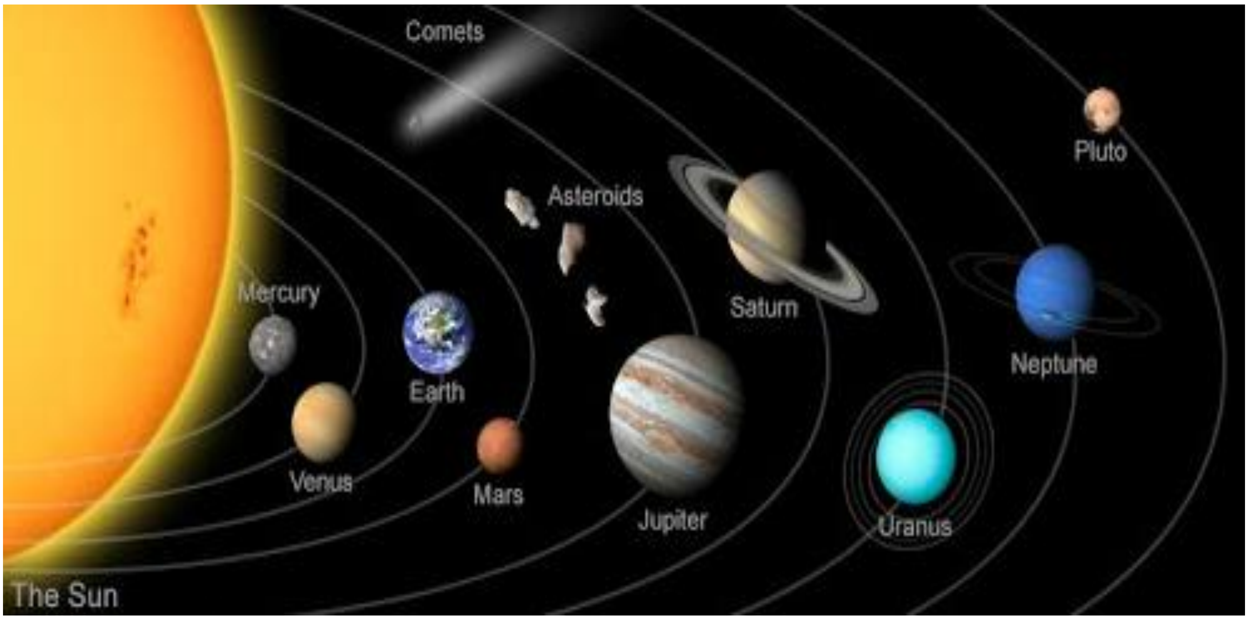

Fig 1: Solar System

Venus

Venus is the brightest object in the sky after the sun and moon because its atmosphere reflects sunlight so well. People often mistake it for a star. Its maximum surface temperature may reach 900F. Venus has no moons and takes 225 days to complete an orbit.

Earth

Earth is the only planet known to support living organisms. Earth's surface is composed of 71% water. Water is necessary for life on Earth. The oceans help maintain Earth's stable temperatures. Earth has one moon and an oxygen rich atmosphere.

Mars

Like Earth, Mars has ice caps at its poles. Mars has the largest volcano in our solar system is Olympus Mons. Olympus Mons is approximately 15 miles high. Mars appears red because of iron oxide, or rust, in its soil. Mars has two moons and takes about two years to complete an orbit.

Jupiter

Jupiter is the largest and most massive planet. It's diameter is 11 times bigger than that of the Earth's. It takes about 12 years for Jupiter to orbit the sun. Jupiter has 16 known moons.

Saturn

Saturn is composed almost entirely of hydrogen and helium. Saturn has many rings made of ice. Saturn's rings are very wide. They extend outward to about 260,000 miles from the surface but are less than 1 mile thick. Saturn has 18 known moons, some of which orbit inside the rings! It takes about 30 years to orbit the sun.

Uranus

Uranus is blue in color due to methane gas in its atmosphere. Uranus has 11 dark rings surrounding it. Uranus has 21 known moons and takes 84 years to complete one orbit.

Neptune

Neptune has the fastest winds in the solar system: up to 2,000 km/hr. Neptune is also blue in color due to methane gas in its atmosphere. Neptune takes 165 years to orbit the sun and has 8 moons.

Pluto

Pluto has only one moon and takes about 249 years to orbit the sun. Part of Pluto's orbit passes inside that of Neptune, so at times Neptune is the planet farthest from the sun. Pluto was located and named in 1930, but today Pluto is no longer considered a planet.

Asteroids

Between the orbits of Mars and Jupiter there exists a belt in which millions of smaller bodies, called asteroids, orbit about the Sun. The largest asteroid, Ceres, which was discovered in 1801, measures about 750 km in diameter. Thousands have been identified and only a few hundred are over 25 km across; most of the asteroids are very small. There are asteroids which periodically pass the Earth quite closely.

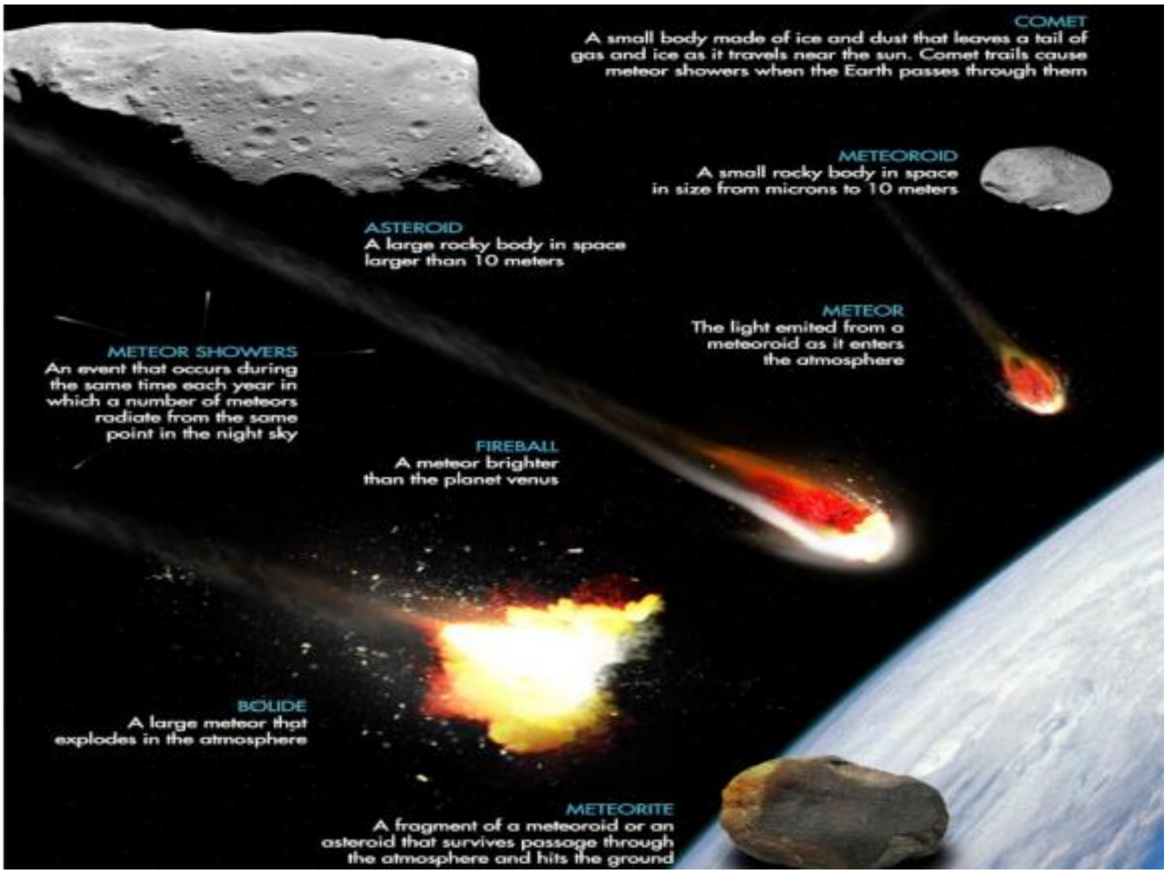

Fig 2: Asteroids, comets and meteoroids

Comets

Comets are mostly rather small objects, composed of frozen gases and solid particles, coming from the outer part of the solar system where they are assumed to have been produced as a by-product in the formation of the solar system. Due to the attraction of the nearest stars, some comets are directed into the inner part of the solar system. When a comet moves in closer to the Sun, it warms up and the nucleus releases gases and dust particles forming a large cloud around the nucleus: the coma. Some of the constituents are expelled more or less radially from the Sun by the solar wind and the radiation pressure of solar light to form the characteristic cometary tail (can be as long as 108 km).

Meteoroids

Meteoroids are too small to be observed in their orbit about the Sun. When they enter the Earth's atmosphere, where they are heated by friction until they melt or vaporize. The luminous phenomenon created this way is called a meteor. Rarely does such a meteoroid survive its entry into the atmosphere and impact on the Earth's surface. The material left is called a meteorite. Though the vast majority of meteoroids are no larger than gravel, occasionally very large meteorites have struck the Earth, producing meteor craters. Sometimes, a great number of meteoroids are found to have the same orbit, they constitute a meteoroid stream, the debris remaining from the breakup of a cometary nucleus. When the Earth is passing through a meteoroid stream a large number of meteors are seen for some days: a meteor shower.

II. REFERENCE FRAMES & COORDINATE SYSTEMS

The location of a point on a line can be described by one coordinate; a point on a plane can be described by two coordinates; a point in a three dimensional volume can be described by three coordinates. In general, the number of coordinates equals the number of dimensions. A coordinate system consists of: a fixed reference point (origin), a set of axes with specified directions and scales and instructions that specify how to label a point in space relative to the origin and axes

A reference frame which is based on the Earth's axis of rotation is taken to denote a position relative to the Earth. The points where this axis crosses the Earth's surface are called the north pole and the south pole. The great circle on the Earth's surface halfway between the poles is the Earth's equator. The great circles passing through the poles are called meridians; they intersect the equator at right angles

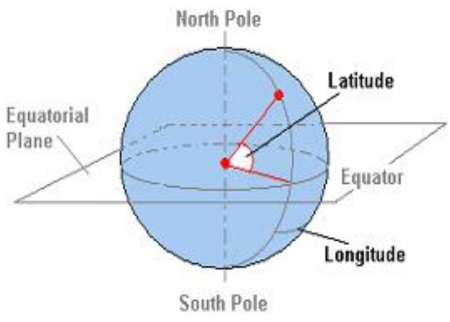

Fig 3: Latitude and Longitude

The geographic longitude (Λ), of a point (P) is defined as the arc length in degrees measured along the equator from the meridian passing through the Royal Observatory at Greenwich, England (G), to the meridian passing through point P. The Longitudes are measured either to the east or west of the Greenwich meridian from 0° to 180°, indicated E or W; positive to the east and negative to the west (W or E can be dropped). The geocentric latitude (Φ), of P is given by the geocentric angle in degrees measured along its meridian, from the equator to P. The Latitudes are measured either to the north or to the south of the equator from 0° to 90°; positive north and negative south of the equator.

Inertial and Non-Inertial Frame of Reference

An inertial reference frame is either at rest or moves with a constant velocity. Non−inertial reference frames:− non−inertial reference frame is a reference frame that is accelerating either in linear fashion or rotating around some axis. Examples:− inertial references frames − A train moving with constant velocity. In the frame of reference of the car, the mass is immobile, and thus has no acceleration. In the non-inertial frame of reference of the car, we still have the weight and tension forces exerted on the mass; these have the same magnitude and direction as in the inertial frame of reference of the groundThe motion of a body can only be described relative to something else—other bodies, observers, or a set of spacetime coordinates. These are called frames of reference. If the coordinates are chosen badly, the laws of motion may be more complex than necessary. For example, suppose a free body that has no external forces acting on it is at rest at some instant. In many coordinate systems, it would begin to move at the next instant, even though there are no forces on it. However, a frame of reference can always be chosen in which it remains stationary. Similarly, if space is not described uniformly or time independently, a coordinate system could describe the simple flight of a free body in space as a complicated zig-zag in its coordinate system. Indeed, an intuitive summary of inertial frames can be given: in an inertial reference frame, the laws of mechanics take their simplest form. In an inertial frame, Newton's first law, the *law of inertia*, is satisfied: Any free motion has a constant magnitude and direction. Newton's second law for a particle takes the mass of a particle and **a** the acceleration of the particle (also a vector) which would be measured by an observer at rest in the frame. The force **F** is the vector sum of all "real" forces on the particle, such as electromagnetic, gravitational, nuclear and so forth. In contrast, Newton's second law in a rotating frame of reference, rotating at angular rate Ω about an axisThe extra terms in the force **F′** are the "fictitious" forces for this frame, whose causes are external to the system in the frame. The first extra term is the Coriolis force, the second the centrifugal force, and the third the Euler force. These terms all have these properties: they vanish when $\Omega = 0$; that is, they are zero for an inertial frame (which, of course, does not rotate); they take on a different magnitude and direction in every rotating frame, depending upon its particular value of $\mathbf{\Omega}$; they are ubiquitous in the rotating frame (affect every particle, regardless of circumstance); and they have no apparent source in identifiable physical sources, in particular, matter. Also, fictitious forces do not drop off with distance (unlike, for example, nuclear forces or electrical forces). For example, the centrifugal force that appears to emanate from the axis of rotation in a rotating frame increases with distance from the axis.All observers agree on the real forces, **F**; only non-inertial observers need fictitious forces. The laws of physics in the inertial frame are simpler because unnecessary forces are not present.

III. CELESTIAL SPHERE

In denoting angular positions of celestial objects, it is convenient to make use of the concept of a fictitious celestial sphere. Has an infinitely large radius, centered at an observer on Earth or at the mass center of the Earth. The remote stars appear to be set on the inner surface of this sphere. It will be clear that only for nearby objects, like spacecraft, different angular positions will be measured on the observer-centered celestial sphere and the Earth-centered celestial sphere In astronomy and navigation, the celestial sphere is an abstract sphere that has an arbitrarily large radius and is concentric to Earth. All objects in the sky can be conceived as being projected upon the inner surface of the celestial sphere, which may be centered on Earth or the observer. If centered on the observer, half of the sphere would resemble a hemispherical screen over the observing location.The celestial sphere is a practical tool for spherical astronomy, allowing astronomers to specify the apparent positions of objects in the sky if their distances are unknown or irrelevant. In the equatorial coordinate system, the celestial equator divides the celestial sphere into two halves: the northern and southern celestial hemispheres.

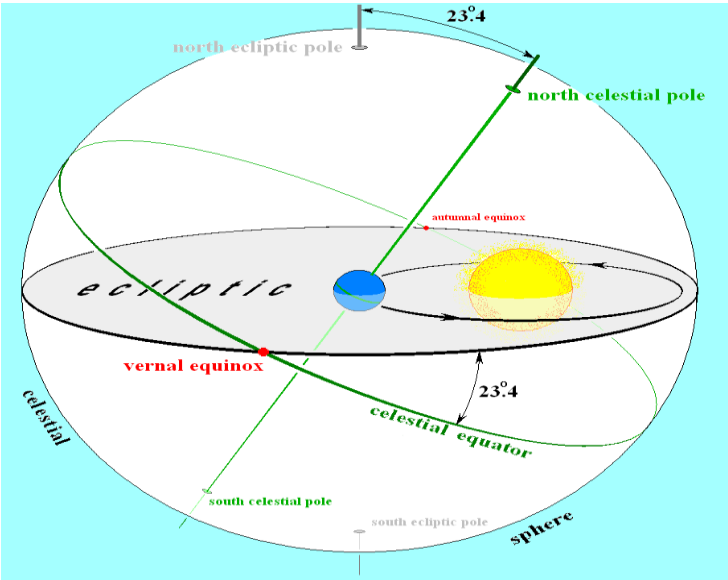

Fig 4: Celestial Sphere

These concepts are important for understanding celestial coordinate systems, frameworks for measuring the positions of objects in the sky. Certain reference lines and planes on Earth, when projected onto the celestial sphere, form the bases of the reference systems. These include the Earth's equator, axis, and orbit. At their intersections with the celestial sphere, these form the celestial equator, the north and south celestial poles, and the ecliptic, respectively.As the celestial sphere is considered arbitrary or infinite in radius, all observers see the celestial equator, celestial poles, and ecliptic at the same place against the background stars.From these bases, directions toward objects in the sky can be quantified by constructing celestial coordinate systems. Similar to geographic longitude and latitude, the equatorial coordinate system specifies positions relative to the celestial equator and celestial poles, using right ascension and declination. The ecliptic coordinate system specifies positions relative to the ecliptic (Earth's orbit), using ecliptic longitude and latitude. Besides the equatorial and ecliptic systems, some other celestial coordinate systems, like the galactic coordinate system, are more appropriate for particular purposes.

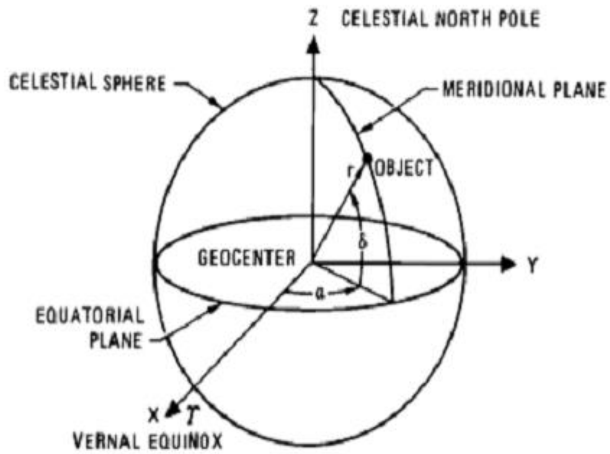

Fig 5: Co-ordinate Axis of Celestial Sphere

When the meridian of an observer on Earth is projected onto the celestial sphere, we speak of the observer's celestial meridian. This celestial meridian, of course, passes through the celestial poles and through a point directly above the observer: his zenith. Owing to the Earth's rotation, the observer's celestial meridian continuously sweeps around the celestial sphere. In another way, the observer watches the celestial sphere rotating about the Earth's spin axis in a westward direction; celestial objects thereby passing the observer's stationary celestial meridian, called as diurnal motion.The two angles needed to define the location of an object along some direction from the origin of the celestial sphere are defined as follows: α (right ascension) = the angle measured eastward in the plane of the equator from a fixed inertial axis in space (vernal equinox) to a plane normal to the equator (meridian), which contains the object,δ(declination) = the angle between the object and equatorial plane measured (positive above the equator) in the meridional plane, which contains the object. r (radial distance) = the distance between the origin of the coordinate system and the location of a point (object) within the coordinate system.To describe the motion of small rockets with respect to the Earth's surface, usually a geocentric rotating reference frame is used. Z-axis is directed along the Earth's spin axis towards the north pole . X-axis is in the Earth's equatorial plane, crossing the upper branch of the Greenwich meridian. The Y -axis lies in the equatorial plane oriented such as to make the reference frame right-handed. In spherical coordinates, position can be expressed by the length of the geocentric radius vector (r), and the geocentric latitude $\boldsymbol{\Phi}$, and geographic longitude, $\boldsymbol{\Lambda}$. This frame is called the geocentric non-rotating equatorial reference frame

IV. ECLIPTICAL SPHERE

If the Sun is observed from the Earth, it is found to possess a second motion in addition to the diurnal motion. The Sun moves eastward among the stars at a rate of about 10per day, returning to its original position on the celestial sphere in one year. The path of the Sun over the celestial sphere is called the ecliptic. The ecliptic plane is inclined to the equatorial plane at an angle E referred to as the obliquity of the ecliptic. At the present time, E= 23°27'.

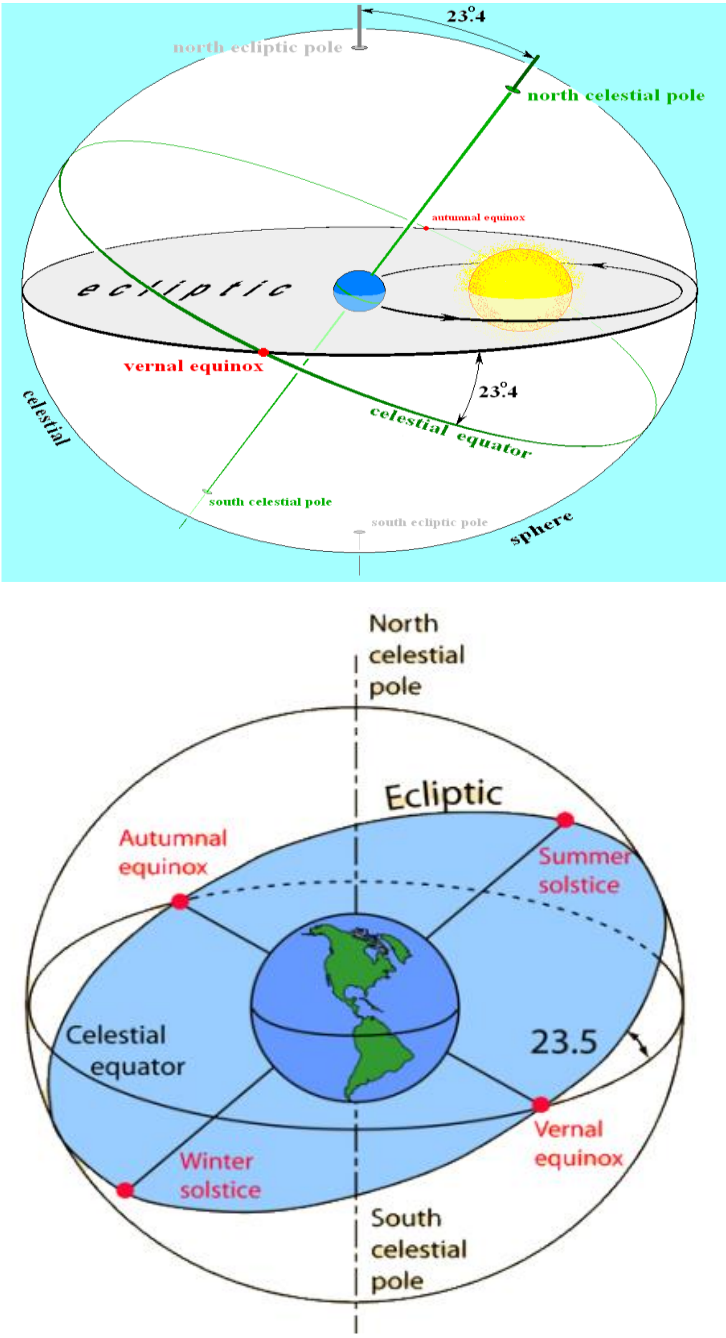

Fig 4: Ecliptical Sphere

The axis of the ecliptic, being the line through the center of the celestial sphere perpendicular to the ecliptic, intersects the celestial sphere in the ecliptic poles. The angular distance between the celestial north pole and the ecliptic north pole equals the angle. Great circles through the ecliptic poles are called circles of celestial longitude. The intersecting line of the equatorial plane and the ecliptic plane plays a fundamental role in the definition of reference frames. This line is called the equinox line because when, for an observer on Earth, the Sun crosses this line, day and night have equal length; 21 March and 23 September each year.These crossing points are called the vernal equinox (First Point of Aries) and the autumnal equinox (Libra), respectively. Position of crossing points are known relative to the stars.To describe planetary positions, or the motion of interplanetary spacecraft, the Sun is more convenient as origin of a reference frame. Ecliptic plane is taken as the XY -plane in a heliocentric reference frame in most cases. The point can serve as the directional reference for the X -axis in a heliocentric reference frame too. In the heliocentric non-rotating ecliptic frame, a position can be described by a heliocentric radius, r, and by the heliocentric longitude and latitude, defined analogously to celestial longitude and latitude in the geocentric ecliptic frame.

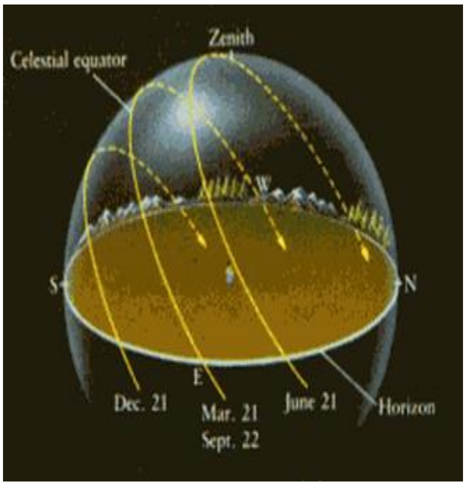

Fig 5: Equinox and Sollistice

The velocity vector of a rocket, satellite or spacecraft can be described by the magnitude of the velocity and by two angles determining the direction of this velocity vector. The local horizontal plane can be defined as the plane normal to the radius vector, r. In the geocentric equatorial reference frame, the north-south direction is defined by the intersection of the plane through the local hour circle with the local horizontal plane.

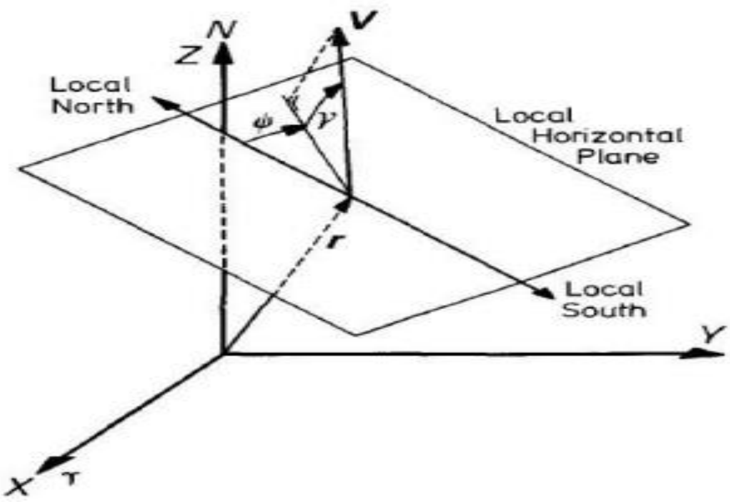

Fig 6: Velocity Vector

The flight path angle, γ, is the angle between the velocity vector, V, and the horizontal plane; varies between -90° and +90°; +90° corresponding with a radially outward directed velocity. The angle between the local north direction and the projection of the velocity vector on the horizontal plane is called the flight path azimuth, $\boldsymbol{\psi}$;measured from the north in a clockwise direction from 0°to 360°. As reference object a particular star can be selected, e.g. Antares. When Antares crosses the observer's meridian we can speak of $0h0m0$ Antares-time. Instead of selecting a particular star, it turns out to be more convenient to use the vernal equinox or the Sun as reference object, resulting in sidereal time and solar time, respectively. As the hour angle of a given point on the celestial sphere differs at a certain epoch for observers with a different geographical longitude, both types of time are local and we speak of local sidereal time and local solar time. Antares is the fifteenth brightest star in the night time sky and the brightest star in the constellation Scorpius, and is often referred to as "the heart of the scorpion".

V. EARTH'S ATMOSPHERE

The earth's atmosphere acts as an insulating layer that protects the earth's surface from the intense light and heat of the sun. The atmosphere is also important because it contains oxygen, which we and other living organisms breathe.

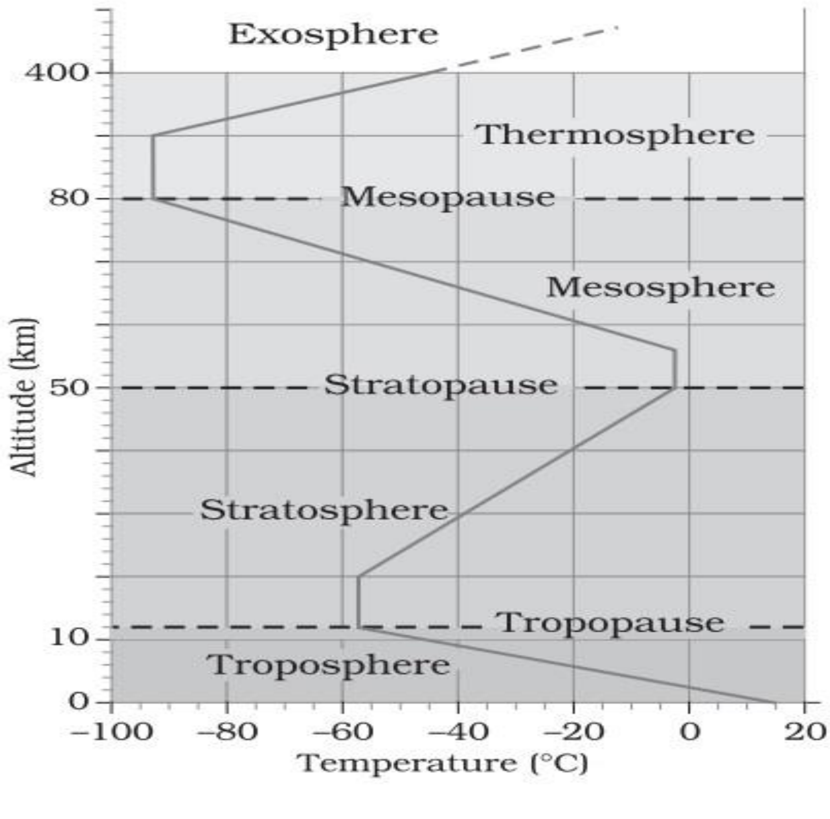

Fig 7: Structure of Atmosphere

There are five layers in the structure of the atmosphere depending upon temperature. These layers are: Troposphere, Stratosphere, Mesosphere, Thermosphere and Exosphere

Troposphere

It is considered as the lowest layer of Earth's atmosphere.The troposphere starts at the surface of the earth and goes up to a height of 7 to 20 km.All-weather occurs within this layer.This layer has water vapor and mature particles. Temperature decreases at the rate of 1 degree Celsius for every 165 m of height. Tropopause separates Troposphere and Stratosphere.

Stratosphere

It is the second layer of the atmosphere found above the troposphere.It extends up to 50 km of height.This layer is very dry as it contains little water vapour. This layer provides some advantages for flight because it is above stormy weather and has steady, strong, horizontal winds.The ozone layer is found in this layer.The ozone layer absorbs UV rays and safeguards earth from harmful radiation. Stratopause separates Stratosphere and Mesosphere.

Mesosphere

The Mesosphere is found above the stratosphere.It is the coldest of the atmospheric layers.The mesosphere starts at 50 km above the surface of Earth and goes up to 85 km.The temperature drops with altitude in this layer.By 80 km it reaches -100 degrees Celsius. Meteors burn up in this layer.The upper limit is called Mesopause which separates Mesosphere and Thermosphere.

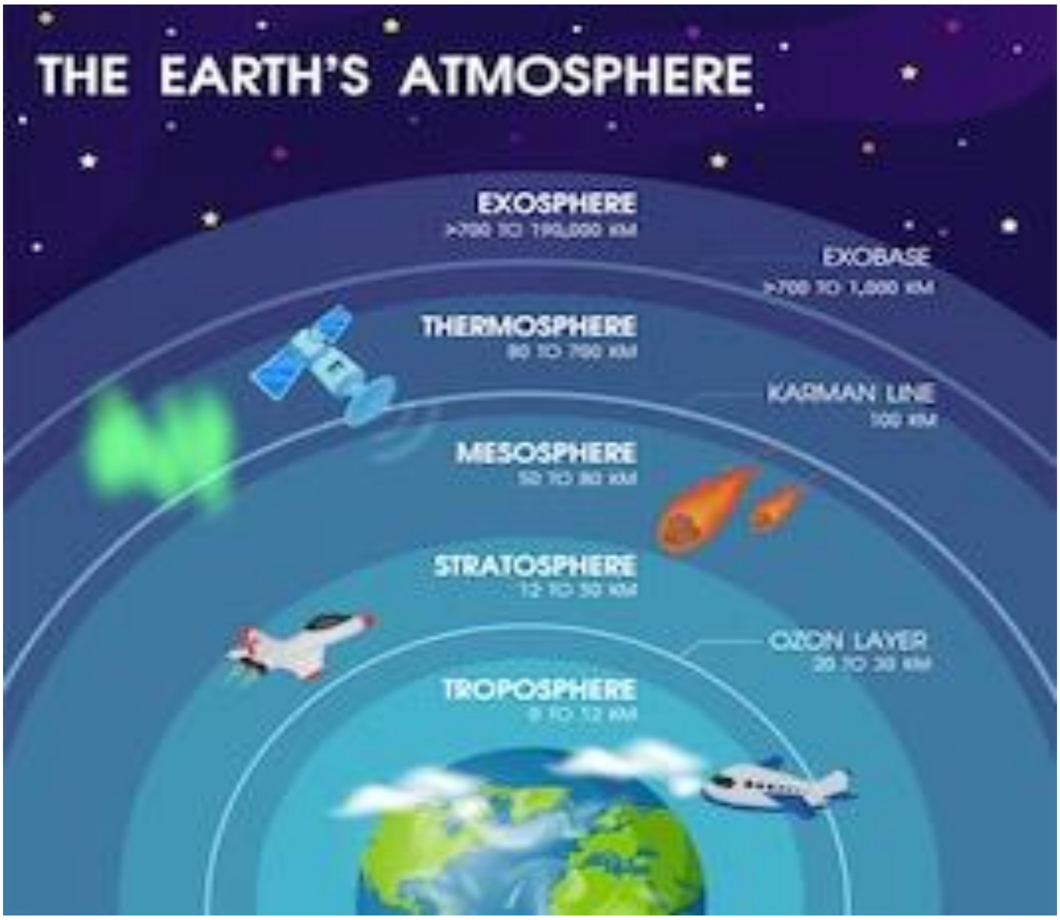

Fig 8: Structure of Atmosphere

Thermosphere

This layer is found above Mesopause from 80 to 400 km.Radio waves that are transmitted from the earth are reflected by this layer.The temperature increases with height. Aurora and satellites occur in this layer.

Ionosphere

The lower Thermosphere is called the Ionosphere.The ionosphere consists of electrically charged particles known as ions.This layer is defined as the layer of the atmosphere of Earth that is ionized by cosmic and solar radiation.It is positioned between 80 and 400 km above the Mesopause.

Exosphere

It is the outermost layer of the atmosphere. The zone where molecules and atoms escape into space is mentioned as the exosphere.It extends from the top of the thermosphere up to 10,000 km.

Earth's Radiation Belts

Van Allen radiation belt, doughnut-shaped zones of highly energetic charged particles trapped at high altitudes in the magnetic field of Earth. The zones were named for James A. Van Allen, the American physicist who discovered them in 1958, using data transmitted by the U.S. Explorer satellite. When investigating solar wind-magnetosphere-ionosphere coupling, it is important to understand how the solar wind, and the interplanetary magnetic field (IMF) frozen into it, behaves as it reaches the Earth. Magnetic reconnection, for example, is a phenomenon whose morphology is governed by the IMF orientation and wields a large influence over many of the processes occurring within the magnetosphere. Exploiting nearly a decade of spacecraft data, primarily from ESA's Cluster mission and NASA's ACE mission, The length of time it takes the solar wind to travel from an upstream observer, situated ~ 240 RE upstream of the Earth, to the near-Earth environment. By isolating those periods when the Clusters pacecraft were within the unimpeded solar wind, the study is able to compare near-Earth magnetic field data to data from the upstream observer ACE.

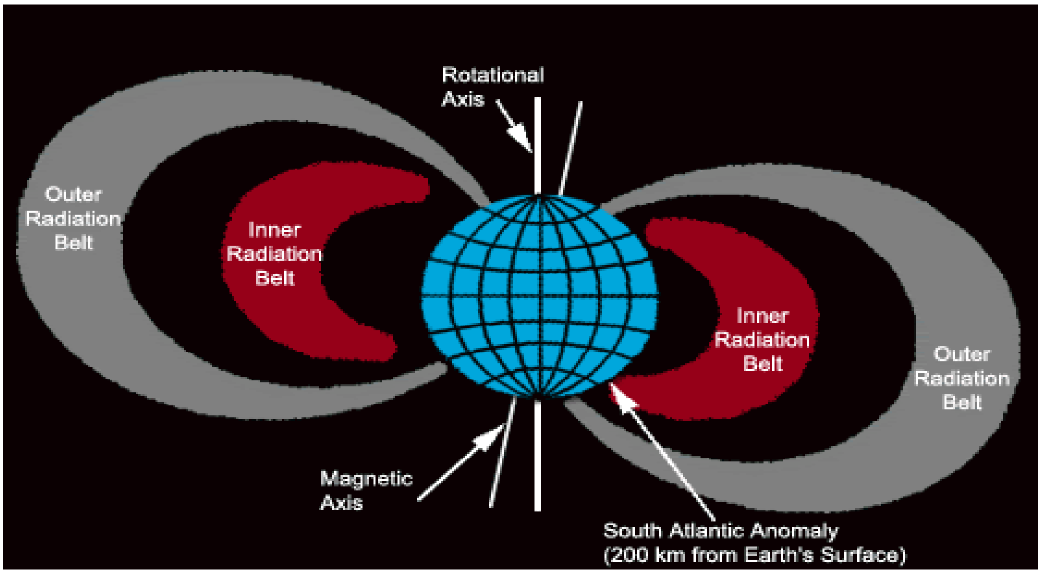

Fig 9: Radiation belt of Atmosphere

Using a cross-correlation method to analyse these data provides nearly 5000 propagation delay times which are then compared to a simple "flat-delay" (i.e. distance/speed) and to the frequently used OMNI web data set. The results of the study show that statistically both methods are similar and provide good estimates, however, there are times when the estimated propagation delay is significantly different from the observed delay.The boundary between the solar wind and the Earth's terrestrial magnetic field is known as the magnetopause. This boundary is an important region for solar wind magneto spheric coupling as it is one of the primary locations for magnetic reconnection.

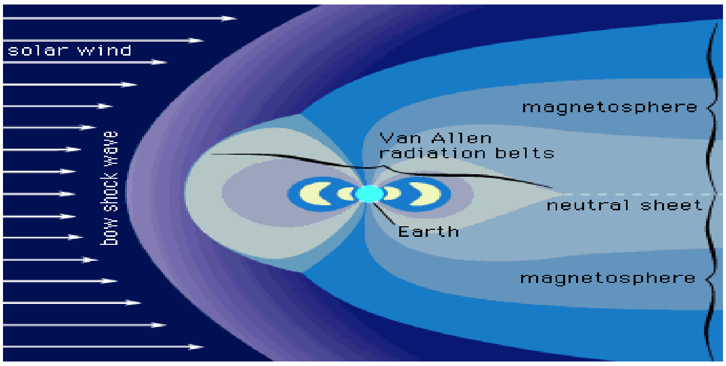

Fig 10: Radiation belt of Atmosphere

To study the magnetopause, it is pivotal to know its location, however, this is non-trivial since the magnetopause is not static but is instead located where there is a pressure balance between the changing solar wind and the magnetosphere. The Cluster satellites are used to determine the location of the magnetopause. Over 2709 individual locations, spread over varying magnetic latitudes and local times, are recorded and compared to four frequently-used magnetopause models. The results show that two of the models overestimate the distance to the magnetopause (by ~ 1 RE) and that two underestimate it (by ~ 0.5 RE and ~ 0.25 RE respectively).

As the solar wind approaches the Earth's magnetosphere it is slowed and a bowshock is formed. Inside this bowshock, the solar wind is turbulent and the orientation of the magnetic field changes through a process known as magnetic draping. An investigation of eight years worth of near-magnetopause magnetic field data, provided by the Cluster mission, is undertaken and the changes in magnetic field orientation are presented. Over the course of 2688 magnetopause crossings, it is found that the upstream IMF conditions have a considerable impact upon the amount of modification of the orientation of the magnetic field as does the location of the recording on the magnetopause. Overall, only 13% of data points exhibit "perfect draping" (where the y- and z- components of the magnetic field are not substantially affected by the magneto sheath traversal)

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SCHOOL OF MECHANICAL ENGINEERING

DEPARTMENT OF AERONAUTICAL ENGINEERING

UNIT – IV - THE GENERAL N-BODY PROBLEM – SAE1402

I. Many Body Problem

The classical problem in celestial mechanics is the determination of the motion of n bodies under their mutual gravitational attractions. These bodies are supposed to possess a spherical symmetry so that they can be regarded as point masses. It is assumed that no other forces act upon these bodies. Here the point mass is considered. For the three-body problem with arbitrary masses, only two kinds of exact particular solutions have been obtained: the straight-line equilibrium solution, the equilateral-triangular equilibrium solution and isosceles-triangular solution (in the case of two equal masses). Consider an inertial reference frame XYZ and a system of n bodies, each with constant mass.

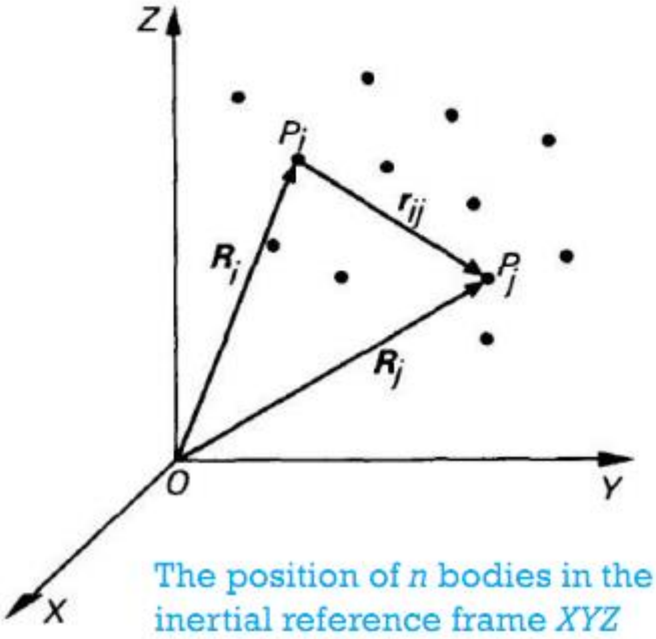

Fig 1: Many Body Problem

The position of a body P_i (i = 1, 2, ... , n), with mass m_i, relative to the inertial frame is determined by its radius vector Ri .According to Newton's laws, the equation of motion of the body Pi relative to the inertial frame is

$$m_i \frac{d^2 \boldsymbol{R}_i}{dt^2} = G \sum_j{}^{*} \frac{m_i m_j}{r_{ij}^3} \boldsymbol{r}_{ij}$$

$$\boldsymbol{F} = \boldsymbol{G} \frac{m_1 m_2}{r^3} \boldsymbol{r}$$

.

$$F = \frac{d}{dt}(mv) = ma = m\frac{d^2 r}{dt^2}$$

$$r_{ij} = R_j - R_i$$

For the actual determination of the motion of each body, we have to integrate numerically the equations of motion.For systems involving more than a few hundred bodies, the integration of these equations is totally impractical. To study the general evolution of such systems, we have to rely on statistical techniques. Only some interesting general features of the dynamical behavior of the bodies can be obtained analytically. These are known as the integrals of motion.

II. Two Body Problem

A more useful and general expression of the gravitational law is in its vector formulation. Consider the masses m and M are moving in an inertial reference frame E1, E2, E3. It is desired to determine the motion of m relative to the larger mass M

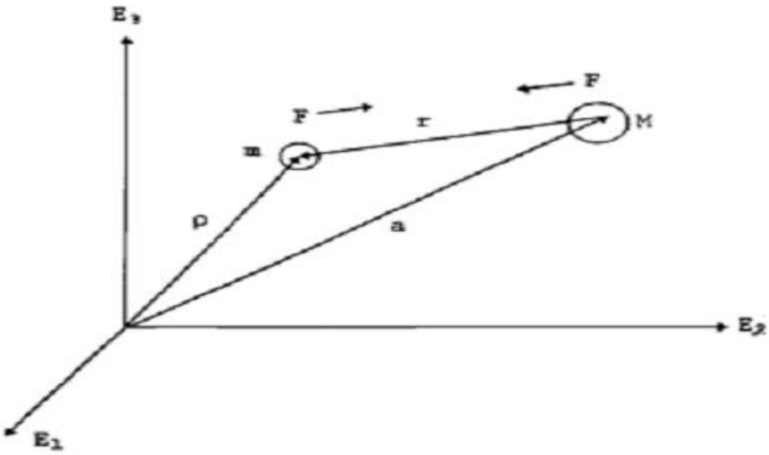

Fig 2: Two Body Problem

The general two body problem results if a is not equal to zero. Then, for the mass M,

$$M\ddot{a} = \frac{GMm\mathbf{r}}{r^3}$$

For the Mass m.

$$m\ddot{\rho} = -\frac{GMm\mathbf{r}}{r^3}$$

Subtracting the equation in above equation, we get

$$\ddot{\mathbf{r}} = -\frac{G(M+m)\mathbf{r}}{r^3}$$

$$\ddot{\mathbf{r}} + \frac{G(M+m)\mathbf{r}}{r^3} = 0$$

In a two body problem , the principal mass M is assumed to be fixed in space. This implies that M >> m, the m does not affect the motion of M. Let o be the origin of the M, assume a =0,

Then the net force on the mass m is

$$\boldsymbol{F} = -\frac{GMm\boldsymbol{r}}{r^3}$$

$$\boldsymbol{F} = -\frac{GMm\boldsymbol{r}}{r^3} = m\ddot{\boldsymbol{r}}$$

Therefore we can write as,

$$\ddot{\boldsymbol{r}} + \frac{GM\boldsymbol{r}}{r^3} = 0$$

Where $\ddot{r} = d^2r/dt^2$, acceleration of mass m relative to the inertial frame. The motion of the two body problem is therefore similar to the many body problem with only effect of definite mass in this two body problem.

$$\ddot{\boldsymbol{r}} + \frac{\mu\boldsymbol{r}}{r^3} = 0$$

Where μ= GM and the mass m << Mass M

Using the Scalar Multiplication , we get

$$\dot{\boldsymbol{r}} \cdot \ddot{\boldsymbol{r}} + \frac{\mu\boldsymbol{r} \cdot \dot{\boldsymbol{r}}}{r^3} = 0$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\dot{\boldsymbol{r}} \cdot \dot{\boldsymbol{r}}}{2}\right) + \frac{\mu}{r^3}\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\boldsymbol{r} \cdot \boldsymbol{r}}{2}\right) = 0$$

$$\frac{(\dot{r})^2}{2} - \frac{\mu}{r} = \varepsilon$$

Where ε is the Specific mechanical energy. The first term is specific kinetic energy and the second term in specific potential energy

III. Lagrangian Points or Liberation Points

In celestial mechanics, the Lagrange points are orbital points near two large co-orbiting bodies. At the Lagrange points the gravitational forces of the two large bodies cancel out in such a way that a small object placed in orbit there is in equilibrium relative to the center of mass of the large bodies. There are five such points, labeled L1 to L5, all in the orbital plane of the two large bodies, for each given combination of two orbital bodies. For instance, there are five Lagrangian points L1 to L5 for the Sun–Earth system, and in a similar way there are five different Lagrangian points for the Earth–Moon system. L1, L2, and L3 are on the line through the centers of the two large bodies, while L4 and L5 each act as the third vertex of an equilateral triangle formed with the centers of the two large bodies. L4 and L5 are stable, which implies that objects can orbit around them in a rotating coordinate system tied to the two large bodies. Several planets have trojan asteroids near their L4 and L5 points with respect to the Sun. Jupiter has more than a million of these trojans. Artificial satellites have been placed at L1 and L2 with respect to the Sun and Earth, and with respect to the Earth and the Moon. The Lagrangian points have been proposed for uses in space exploration.

The five Lagrange points are labeled and defined as follows:

L1 point

The L1 point lies on the line defined by the two large masses M1 and M2, and between them. It is the point where the gravitational attraction of M2 partially cancels that of M1. An object that orbits the Sun more closely than Earth would normally have a shorter orbital period than Earth, but that ignores the effect of Earth's own gravitational pull. If the object is directly between Earth and the Sun, then Earth's gravity counteracts some of the Sun's pull on the object, and therefore increases the orbital period of the object. The closer to Earth the object is, the greater this effect is. At the L1 point, the orbital period of the object becomes exactly equal to Earth's orbital period. L1 is about 1.5 million kilometers from Earth, or 0.01 au, 1/100th the distance to the Sun.

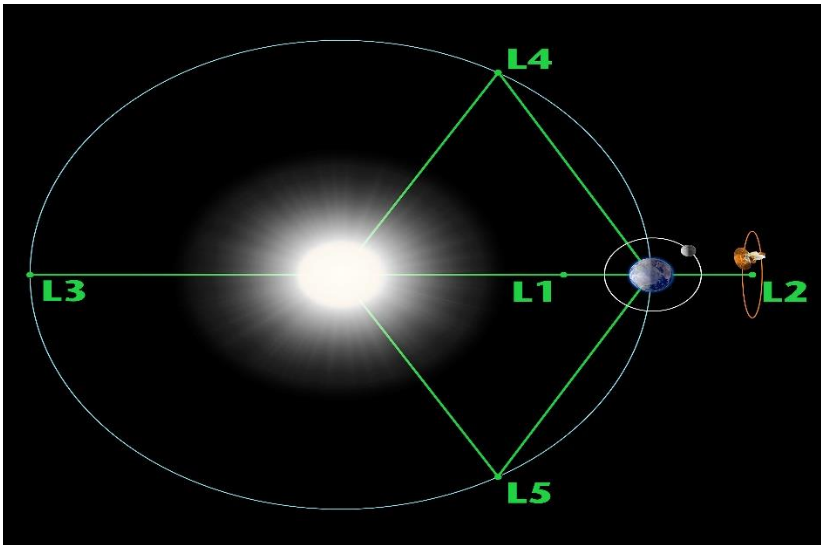

Fig 3: Liberation Points

L2 point

The L2 point lies on the line through the two large masses, beyond the smaller of the two. Here, the gravitational forces of the two large masses balance the centrifugal effect on a body at L2. On the opposite side of Earth from the Sun, the orbital period of an object would normally be greater than that of Earth. The extra pull of Earth's gravity decreases the orbital period of the object, and at the L2 point that orbital period becomes equal to Earth's. Like L1, L2 is about 1.5 million kilometers or 0.01 au from Earth.

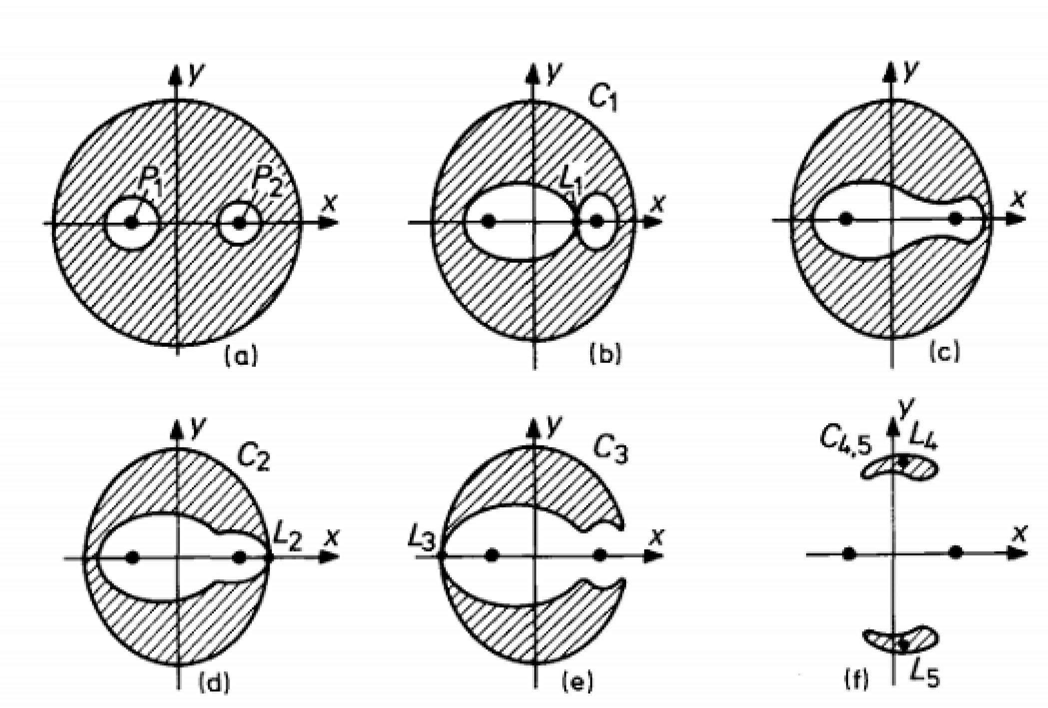

Fig 4: Modelling of Liberation Points

L3 point

The L3 point lies on the line defined by the two large masses, beyond the larger of the two. Within the Sun–Earth system, the L3 point exists on the opposite side of the Sun, a little outside Earth's orbit and slightly further from the Sun than Earth is. This placement occurs because the Sun is also affected by Earth's gravity and so orbits around the two bodies' barycenter, which is well inside the body of the Sun. An object at Earth's distance from the Sun would have an orbital period of one year if only the Sun's gravity is considered. But an object on the opposite side of the Sun from Earth and directly in line with both "feels" Earth's gravity adding slightly to the Sun's and therefore must orbit a little further from the Sun in order to have the same 1-year period. It is at the L3 point that the combined pull of Earth and Sun causes the object to orbit with the same period as Earth, in effect orbiting an Earth+Sun mass with the Earth-Sun barycenter at one focus of its orbit.

L4 and L5 points

The L4 and L5 points lie at the third corners of the two equilateral triangles in the plane of orbit whose common base is the line between the centers of the two masses, such that the point lies behind (L5) or ahead (L4) of the smaller mass with regard to its orbit around the larger mass.The triangular points (L4 and L5) are stable equilibria, provided that the ratio of M1/M2 is greater than 24.96.This is the case for the Sun–Earth system, the Sun–Jupiter system, and, by a smaller margin, the Earth–

Moon system. When a body at these points is perturbed, it moves away from the point, but the factor opposite of that which is increased or decreased by the perturbation (either gravity or angular momentum-induced speed) will also increase or decrease, bending the object's path into a stable, kidney bean-shaped orbit around the point (as seen in the co rotating frame of reference).In contrast to L4 and L5, where stable equilibrium exists, the points L1, L2, and L3 are positions of unstable equilibrium. Any object orbiting at L1, L2, or L3 will tend to fall out of orbit; it is therefore rare to find natural objects there, and spacecraft inhabiting these areas must employ station keeping in order to maintain their position.

Sphere of Influence

The motion of an interplanetary spacecraft is governed by the attracting forces of all planets and the Sun. Trajectory can be approximated by accounting only for three gravitational fields: those of the Earth, the Sun and the target planet. We then imagine the trajectory to be composed of three successive two-body trajectories; in each trajectory the spacecraft is assumed to be attracted by only one celestial body. Using certain criterion we can determine the distance from the Earth, and from the target planet, where the switch between the successive two-body trajectories has to be made. Consider the motion of the spacecraft with mass mc relative to a non-rotating reference frame with its origin at the Earth's center. We assume that the only disturbing body is the Sun. The masses of Sun and Earth are denoted by ms and me, respectively.

For convenience, we approximate this surface by a sphere with radius equal to the maximum value of rec· This sphere is called the sphere of influence or the activity sphere of the Earth.

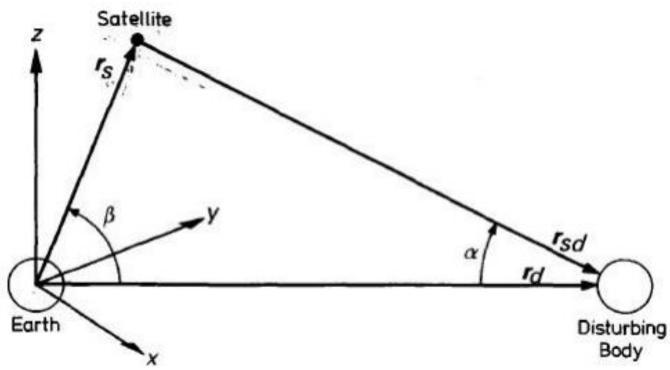

Fig 5: Relative positions of Earth, satellite and disturbing body

Sphere of influence can be determined for each planet and is given by

$$R_{s.i} = r_{ps}\left(\frac{m_p}{m_s}\right)^{2/5}$$

Where, $R_{s.i}$ - radius of sphere of influence

r_{ps} - distance between the planet and the Sun

The concept of a sphere of influence was introduced by Laplace in his studies on the motion of comets in the immediate neighbourhood of the planet Jupiter. It is widely used for feasibility studies in interplanetary spaceflight

IV. Satellite

A satellite is a moon, planet or machine that orbits a planet or star. For example, Earth is a satellite because it orbits the sun. Likewise, the moon is a satellite because it orbits Earth. The path along which satellite moves in the space around earth are called orbits.

Characteristics of orbit are

- **Apogee:** Farthest point on the orbit of a satellite from earth.
- **Perigee**: Nearest point on the orbit of a satellite from earth.
- **Inclination:** It is determined by the angle it makes with the equator.

A Satellite can move in three types of orbits- Based on inclination namely

Equatorial orbit

It lies in the equatorial plane of the earth. This orbit is most useful orbit for communication purposes.

Fig 6 Equatorial orbit

Polar orbit

The polar orbit is from north pole to south pole.

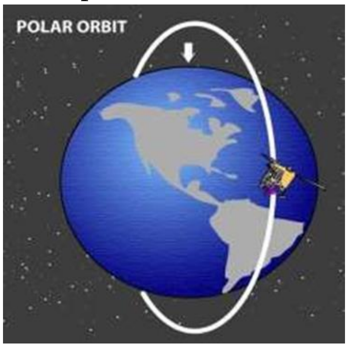

Fig 7 Polar orbit

Inclined orbit

The orbit with an inclination angles is called as Inclined orbit.

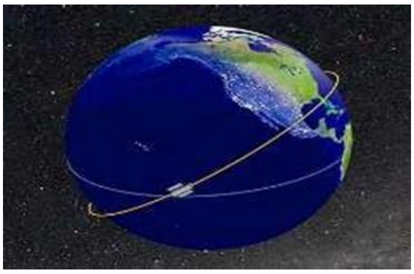

Fig 8 Inclined orbit

The orbit is further classified into three types: Based on Range
GEO- Geo Earth orbits
MEO- Medium Earth orbits
LEO- Low Earth Orbits

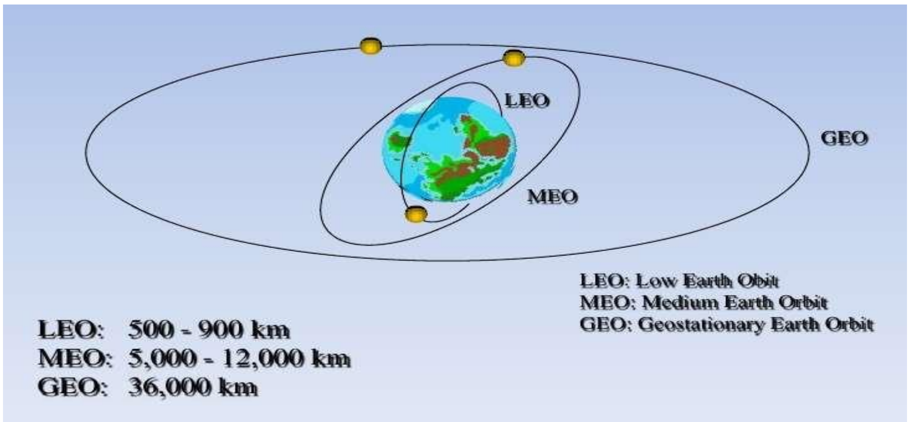

Fig 9 GEO,MEO,LEO orbit

The Characteristics of the orbits- Based on Range

GEO	MEO	LEO
These are very far away from earth	These are little far from earth	These are much closer to earth
These are placed at the height of 35,786km from the earth surface	These are placed at the height in between8,000 km to18,000 km from the earth surface	These are placed at the height in between 500 to 1,500 km from the earth surface
Here satellite revolves with same angular velocity as the earth rotation	In this orbit satellite revolves faster than earth	LEO satellites don't stay in fixed position relative to the surface
Maximum time taken to complete one revolution is around 23H:56M:4s	MEO satellites are visible for particular period of time, usually between 2 to 8 hours.	These are only visible for 15 to 20 minutes each pass.
Larger coverage area ,a single satellite can cover 42% of earth	Not as much as GEO satellite	Not as much as GEO ,MEO satellites

Tab 1: GEO,MEO,LEO Charactertistics

Satellite Architecture

A communications satellite is an artificial satellite that relays and amplifies radio telecommunications signals via a transponder; it creates a communication channel between a source transmitter and a receiver at different locations on Earth. Communications satellites are used for television, telephone, radio, internet, and military applications. There are over 2,000 communications satellites in Earth's orbit, used by both private and government organizations.

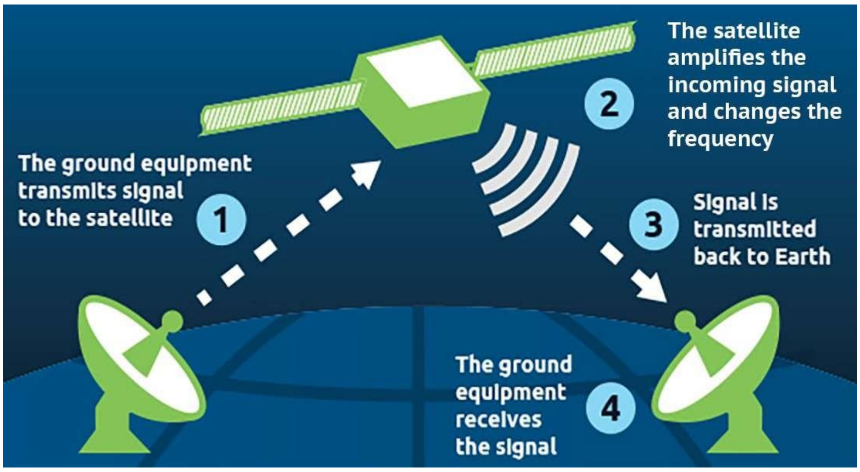

Fig 9 Data transfer of satellite to ground station and vice versa

The major subsystem of satellite are

Solar panels: They charge the batteries and supply the electric power for the spacecraft.

Communication subsystems: This is a set of transponders that receive the uplink signals and Transmit them to the earth.

Telemetry, tracking and command subsystem: It monitors onboard conditions such as temperature and battery voltage and transmit them to ground station for analysis.

Attitude control subsystem: It provides stabilization in orbit and senses change in orientation

Propulsion subsystem: The jet thrusters and apogee kick motor (AKM) are part of propulsion subsystem and are c ommanded from ground.

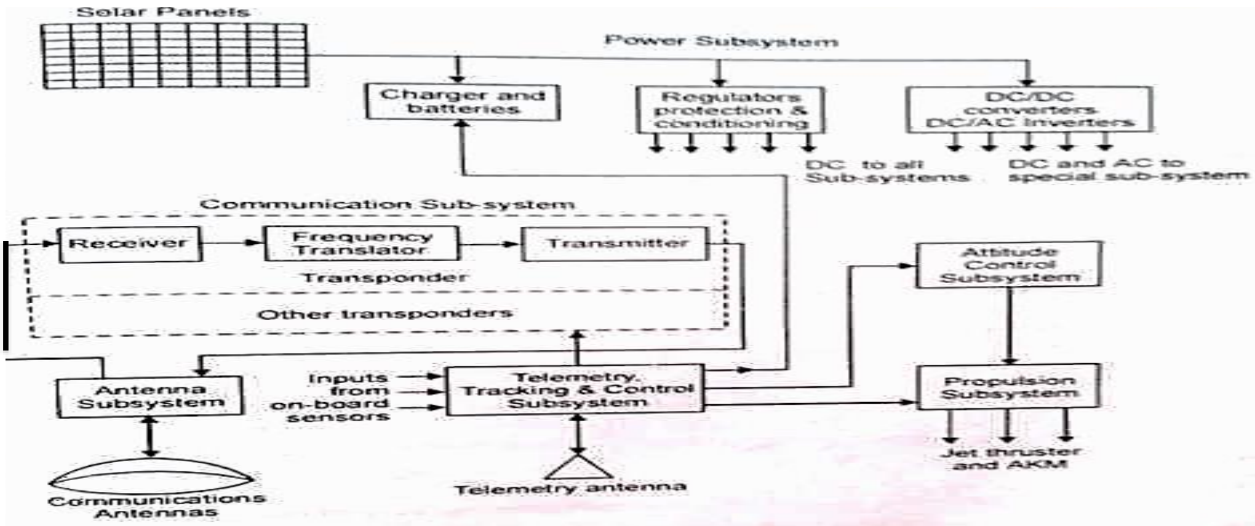

Fig 10 Satellite Architecture

Advantages

- The coverage area of a satellite greatly exceeds that of a terrestrial system.
- Transmission cost of a satellite is independent of the distance from the center of the coverage area.
- Satellite to Satellite communication is very precise.
- Higher Bandwidths are available for use

Disadvantage

- Launching satellites into orbit is costly.
- Satellite bandwidth is gradually becoming used up.
- There is a larger propagation delay in satellite communication than in terrestrial.

Major problems for satellites

- Positioning in orbit
- Stability
- Power
- Communications
- Harsh Environment

Satellite Transmission Bands

C Band are mostly used. It’s capacity is low and terrestrial interference is problem. In Ku band, rain interference is the problem. In Ka band, equipment needed to use the band is very expensive.

Frequency Band	Downlink	Uplink
C	3.7-4.2 GHz	5.92-6.42 GHz
Ku	11.7-12.2 GHz	14.0-14.5 GHz
Ka	17.7-21.2 GHz	27.5-31.0 GHz

Tab 2 : Frequency bands

Features of geostationary satellite

- The orbit is circular

- The orbit is in equatorial plane i.e.directly above the equator and thus inclination is zero.
- The angular velocity of the satellite is equal to angular velocity of earth
- Period of revolution is equal to period of rotation of earth.
- Completes one revolution around the earth in exactly one day i.e. 23 hours, 56 Minutes and 4.1 seconds There is ONLY one geostationary orbit.

Features of geosynchronous satellite

- There is a difference between the geostationary and geosynchronous orbits.
- We should note that while other orbits may be many, there is ONLY ONE Equatorial orbit, i.e. the orbit which is directly above the earth's equator.
- Sometimes we send a satellite in the space which though has a period of revolution is equal to period of rotation of earth, but its orbit is neither equatorial nor Circular.
- So, this satellite will finish one revolution around the earth in exactly one day i.e. 23 hours, 56 Minutes and 4.1 seconds, yet it does NOT appear stationary from the earth.
- It looks oscillating but NOT stationary and that is why it is called **Geosynchronous.**
- The orbit is NOT circular
- The orbit is NOT in equatorial plane, (directly above the equator), it's in inclined orbit
- The angular velocity of the satellite is equal to angular velocity of earth
- Period of revolution is equal to period of rotation of earth.
- Finish one revolution around the earth in exactly one day i.e. 23 hours, 56 Minutes and 4.1 seconds There are many geosynchronous orbits.

SCHOOL OF MECHANICAL ENGINEERING

DEPARTMENT OF AERONAUTICAL ENGINEERING

UNIT – V- ORBIT DYNAMICS – SAE1402

I. Kelperian Orbits

Kepler’s First Law

The prevailing view during the time of Kepler was that all planetary orbits were circular. The data for Mars presented the greatest challenge to this view and that eventually encouraged Kepler to give up the popular idea. Kepler’s first law states that every planet moves along an ellipse, with the Sun located at a focus of the ellipse. An ellipse is defined as the set of all points such that the sum of the distance from each point to two foci is a constant, shows an ellipse and describes a simple way to create it.

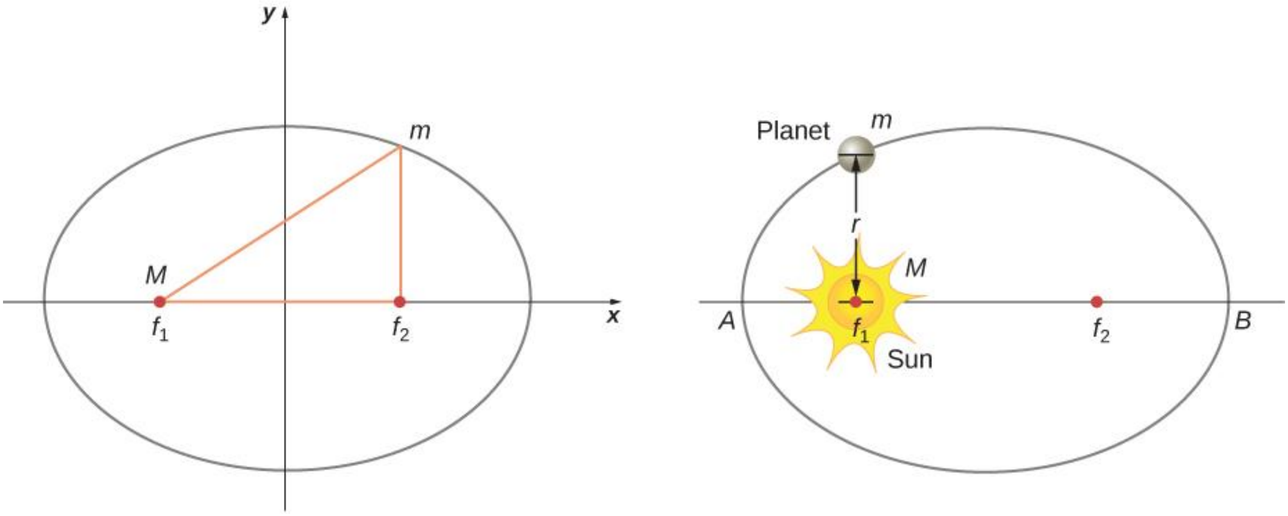

Fig 1 : Kelper’s First Law

Kepler’s Second Law

Kepler’s second law states that a planet sweeps out equal areas in equal times, that is, the area divided by time, called the areal velocity, is constant. The time it takes a planet to move from position A to B, sweeping out area A1A1, is exactly the time taken to move from position C to D, sweeping area A2A2, and to move from E to F, sweeping out area A3A3. These areas are the same: A1=A2=A3

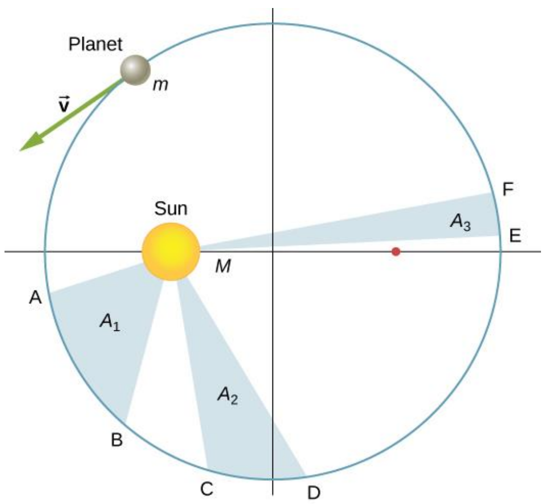

Fig 2 : Kelper’s second Law

Kepler’s Third Law

Kepler’s third law states that the square of the period is proportional to the cube of the semi-major axis of the orbit. In Kepler’s third law for the special case of a circular orbit and gives us the period of a circular orbit of radius *r* about Earth:

T=2π√r3GME.T=2πr3GME.

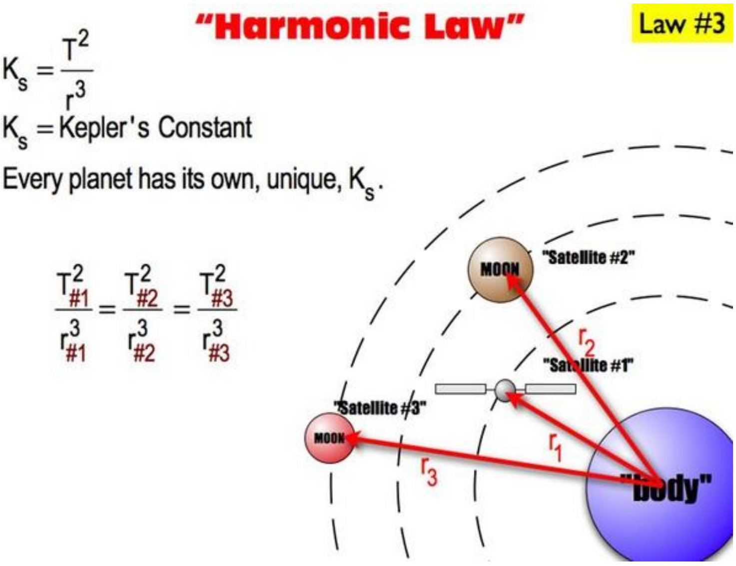

Fig 3 : Kelper’s third Law

For an ellipse, recall that the semi-major axis is one-half the sum of the perihelion and the aphelion. For a circular orbit, the semi-major axis (*a*) is the same as the radius for the orbit. In fact, gives us Kepler’s third law if we simply replace *r* with *a* and square both sides.

T2=4π2GMa3T2=4π2GMa3

We have changed the mass of Earth to the more general *M*, since this equation applies to satellites orbiting any large mass.

II. Orbital Elements

Orbital elements are the parameters required to uniquely identify a specific orbit. In celestial mechanics these elements are considered in two-body systems using a Kepler orbit. There are many different ways to mathematically describe the same orbit, but certain schemes, each consisting of a set of six parameters, are commonly used in astronomy and orbital mechanics.A real orbit and its elements change over time due to gravitational perturbations by other objects and the effects of general relativity. A Kepler orbit is an idealized, mathematical approximation of the orbit at a particular time.Hence, this is also called as Kelperian elements.

The traditional orbital elements are the six Keplerian elements, after Johannes Kepler and his laws of planetary motion. When viewed from an inertial frame, two orbiting bodies trace out distinct trajectories. Each of these trajectories has its focus at the common center of mass. When viewed from a non-inertial frame centred on one of the bodies, only the trajectory of the opposite body is apparent; Keplerian elements describe these non-inertial trajectories. An orbit has two sets of Keplerian elements depending on which body is used as the point of reference. The reference body is called the *primary*, the other body is called the *secondary*. The primary does not necessarily possess more mass than the secondary, and even when the bodies are of equal mass, the orbital elements depend on the choice of the primary.

Two elements define the shape and size of the ellipse:

- Eccentricity (e)—shape of the ellipse, describing how much it is elongated compared to a circle (not marked in diagram).
- Semimajor axis (a)—the sum of the periapsis and apoapsis distances divided by two. For classic two-body orbits, the semimajor axis is the distance between the centers of the bodies, not the distance of the bodies from the center of mass.

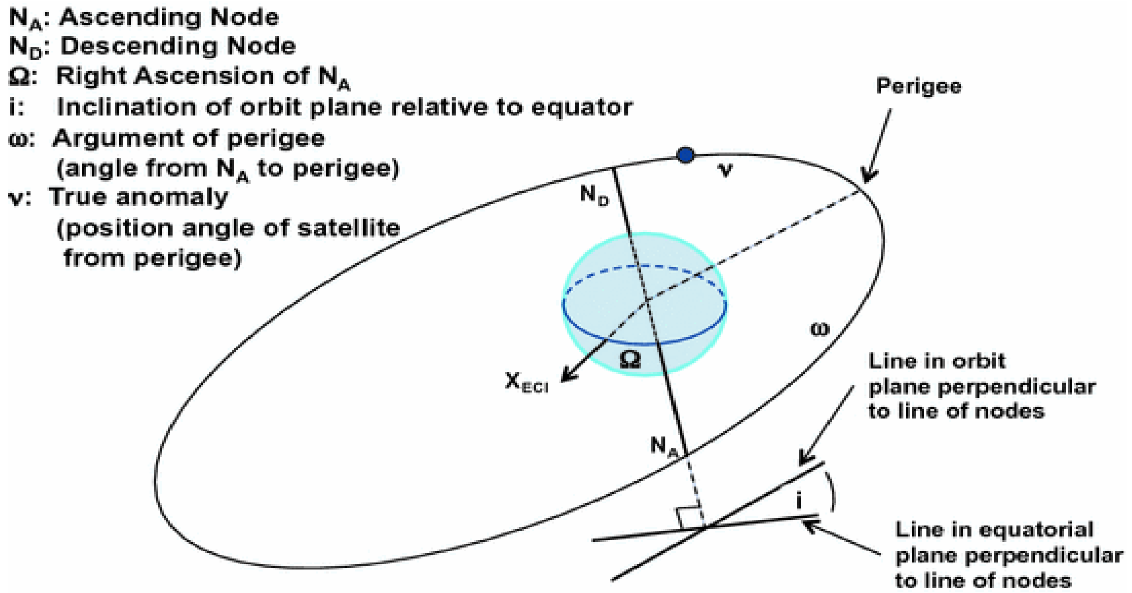

Fig 4 : Kelperian elements

Two elements define the orientation of the orbital plane in which the ellipse is embedded:

- Inclination (i)—vertical tilt of the ellipse with respect to the reference plane, measured at the ascending node (where the orbit passes upward through the reference plane, the green angle i in the diagram). Tilt angle is measured perpendicular to line of intersection between orbital plane and reference plane. Any three points on an ellipse will define the ellipse orbital plane. The plane and the ellipse are both two-dimensional objects defined in three-dimensional space.
- Longitude of the ascending node (Ω)—horizontally orients the ascending node of the ellipse (where the orbit passes upward through the reference plane, symbolized by ☊) with respect to the reference frame's vernal point (symbolized by ♈□). This is measured in the reference plane, and is shown as the green angle Ω in the diagram.

The remaining two elements are as follows:

- Argument of periapsis (ω) defines the orientation of the ellipse in the orbital plane, as an angle measured from the ascending node to the periapsis (the closest point the satellite object comes to the primary object around which it orbits, the blue angle ω in the diagram).

- True anomaly (ν, θ, or f) at epoch (t_0) defines the position of the orbiting body along the ellipse at a specific time (the "epoch").

The mean anomaly M is a mathematically convenient fictitious "angle" which varies linearly with time, but which does not correspond to a real geometric angle. It can be converted into the true anomaly ν, which does represent the real geometric angle in the plane of the ellipse, between periapsis (closest approach to the central body) and the position of the orbiting object at any given time. Thus, the true anomaly is shown as the red angle ν in the diagram, and the mean anomaly is not shown.The angles of inclination, longitude of the ascending node, and argument of periapsis can also be described as the Euler angles defining the orientation of the orbit relative to the reference coordinate system.Note that non-elliptic trajectories also exist, but are not closed, and are thus not orbits. If the eccentricity is greater than one, the trajectory is a hyperbola. If the eccentricity is equal to one and the angular momentum is zero, the trajectory is radial. If the eccentricity is one and there is angular momentum, the trajectory is a parabola.

III. Pertubations

In astronomy, perturbation is the complex motion of a massive body subject to forces other than the gravitational attraction of a single other massive body. The other forces can include a third (fourth, fifth, etc.) body, resistance, as from an atmosphere, and the off-center attraction of an oblate or otherwise misshapen body.

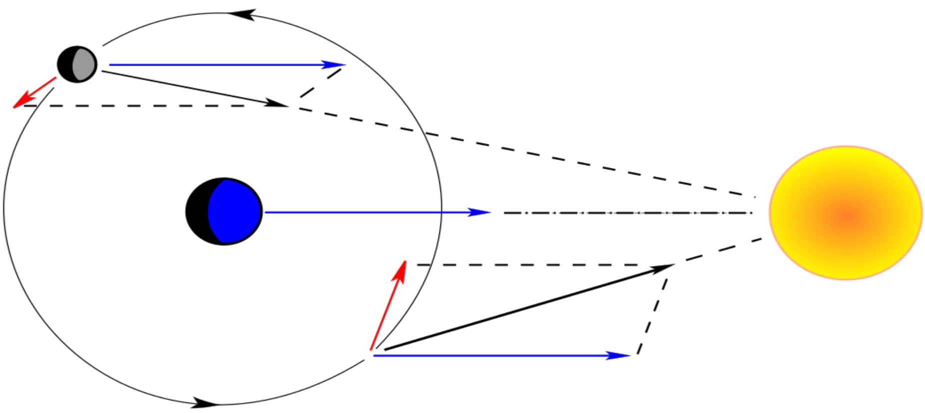

Fig 5: Pertubations

General perturbations

In methods of general perturbations, general differential equations, either of motion or of change in the orbital elements, are solved analytically, usually by series expansions. The result is usually expressed in terms of algebraic and trigonometric functions of the orbital elements of the body in question and the perturbing bodies. This can be applied generally to many different sets of conditions, and is not specific to any particular set of gravitating objects.

Special perturbations

In methods of special perturbations, numerical datasets, representing values for the positions, velocities and accelerative forces on the bodies of interest, are made the basis of numerical integration of the differential equations of motion.In effect, the positions and velocities are perturbed directly, and no attempt is made to calculate the curves of the orbits or the orbital elements.Special perturbations can be applied to any problem in celestial mechanics, as it is not limited to cases where the perturbing forces are small. Once applied only to comets and minor planets, special perturbation methods are now the basis of the most accurate machine-generated planetary ephemerides of the great astronomical almanacs. Special perturbations are also used for modeling an orbit with computers.

Cowell's Pertubations

Cowell's formulation (so named for Philip H. Cowell, who, with A.C.D. Cromellin, used a similar method to predict the return of Halley's comet) is perhaps the simplest of the special perturbation methods.In a system of mutually interacting bodies, this method mathematically solves for the Newtonian forces on body.

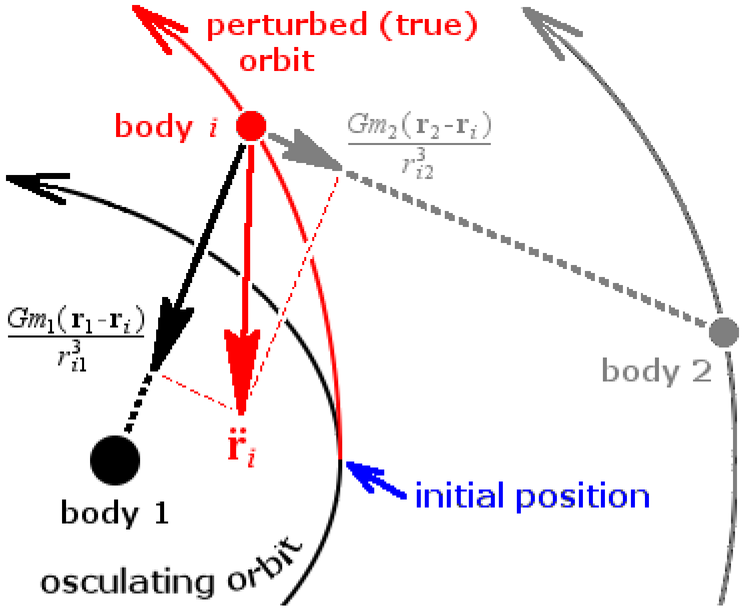

Fig 6: Cowell's Pertubations

This equation is resolved into components in these are integrated numerically to form the new velocity and position vectors as the simulation moves forward in time. The advantage of Cowell's method is ease of application and programming. A disadvantage is that when perturbations become large in magnitude (as when an object makes a close approach to another) the errors of the method also become large. Another disadvantage is that in systems with a dominant central body, such as the Sun, it is necessary to carry many significant digits in the arithmetic because of the large difference in the forces of the central body and the perturbing bodies.

Encke's method

Encke's method begins with the osculating orbit as a reference and integrates numerically to solve for the variation from the reference as a function of time. Its advantages are that perturbations are generally small in magnitude, so the integration can proceed in larger steps (with resulting lesser errors), and the method is much less affected by extreme perturbations. Its disadvantage is complexity; it cannot be used indefinitely without occasionally updating the osculating orbit and continuing from there, a process known as rectification.

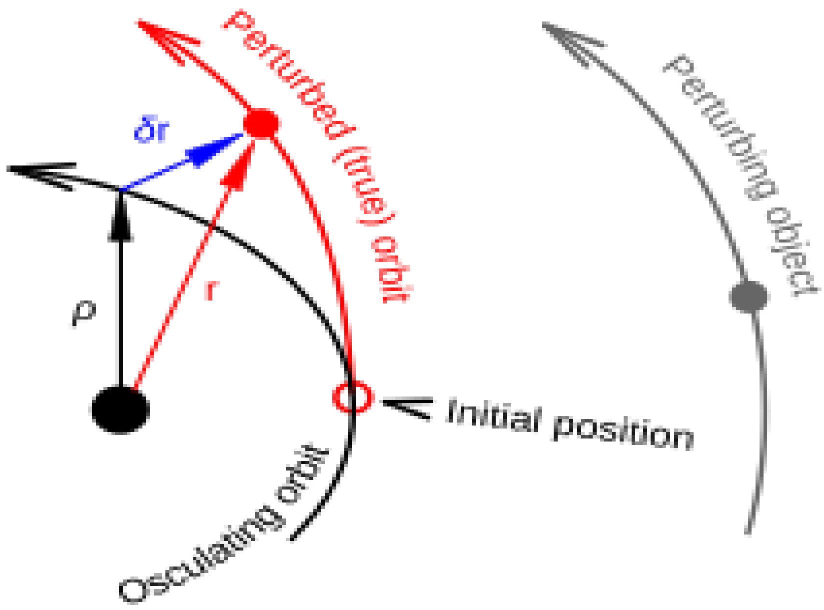

Fig 7: Encke's Pertubations

Since the osculating orbit is easily calculated by two-body methods, and the difference of two nearly equal vectors, and further manipulation is necessary to avoid the need for extra significant digits.

IV. Relationship between orbital elements and position and velocity

The instantaneous position and velocity of body in its motion about body can be described by its rectangular coordinates and velocity components

There exist one-to-one relationships between these three sets of parameters. In one respect the last set is entirely different from the first two: the six orbital elements are constant during the motion. Therefore, the general scheme to compute the position of P, at some time t is as follows. First the orbital elements are computed at to when the position and velocity of P, are known. Because these elements are constant, they take the same value at time t, and by an inverse transformation the position and velocity at time t.

For the transformations between the three sets of parameters mcntioned above, six sets of transformation relations are needed. They can be derived easily. As an example, we will derive the transformation relations to compute rectangular coordinates and velocity components from orbital elements. The three sets of transformation relations only hold for elliptic orbits, but the derivations for parabolic and hyperbolic orbits are essentially the same. In all cases, the non-rotating geocentric equatorial frame is taken as reference frame. Rectangular coordinates from orbital elements When the orbital elements are known, the solution of Kepler's equation for a certain time to provides us with the value of E at that time. we then obtain the value of B at that time. For convenience, we now select a right-handed Cartesian reference frame erg with its origin coinciding with the origin of the geocentric xyz-frame. The 01-plane coin-cides with the orbital plane and the positive faxis points towards the perigee. In this frame, the coordinates of body P, are given by

$$\xi = r\cos\theta, \qquad \eta = r\sin\theta, \qquad \zeta = 0,$$

For the transformations between the three sets of parameters mcntioned above, six sets of transformation relations are needed. They can be derived easily. As an example, we will derive the transformation relations to compute rectangular coordinates and velocity components from orbital elements. The three sets of transformation relations only hold for elliptic orbits, but the derivations for parabolic and hyperbolic orbits are essentially the same. In all cases, the non-rotating geocentric equatorial frame is taken as reference frame. Rectangular coordinates from orbital elements When the orbital elements are known, the solution of Kepler's equation for a certain time to provides us with the value. For convenience, we now select a right-handed Cartesian reference frame erg with its origin coinciding with the origin of the geocentric xyz-frame. The 01-plane coin-cides with the orbital plane and the positive axis points towards the perigee

$$(x, y, z) = (\xi, \eta, \zeta)\mathbf{A}_\omega \mathbf{A}_i \mathbf{A}_\Omega,$$

where the rotation matrices, $\mathbf{A}_\Omega$, $\mathbf{A}_i$ and $\mathbf{A}_\omega$, are given by

$$\mathbf{A}_\Omega = \begin{bmatrix} \cos\Omega & \sin\Omega & 0 \\ -\sin\Omega & \cos\Omega & 0 \\ 0 & 0 & 1 \end{bmatrix}, \qquad \mathbf{A}_i = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos i & \sin i \\ 0 & -\sin i & \cos i \end{bmatrix},$$

$$\mathbf{A}_\omega = \begin{bmatrix} \cos\omega & \sin\omega & 0 \\ -\sin\omega & \cos\omega & 0 \\ 0 & 0 & 1 \end{bmatrix}.$$

Evaluation of the matrix multiplication yields

$$(x, y, z) = (\xi, \eta, \zeta)\begin{bmatrix} l_1 & m_1 & n_1 \\ l_2 & m_2 & n_2 \\ l_3 & m_3 & n_3 \end{bmatrix},$$

where

$$l_1 = \cos\omega \cos\Omega - \sin\omega \sin\Omega \cos i,$$

$$m_1 = \cos\omega \sin\Omega + \sin\omega \cos\Omega \cos i,$$

$$n_1 = \sin\omega \sin i,$$

$$l_2 = -\sin\omega \cos\Omega - \cos\omega \sin\Omega \cos i,$$

$$m_2 = -\sin\omega \sin\Omega + \cos\omega \cos\Omega \cos i,$$

$$n_2 = \cos\omega \sin i,$$

$$l_3 = \sin\Omega \sin i,$$

$$m_3 = -\cos\Omega \sin i,$$

$$n_3 = \cos i.$$

Because P_i always is in the $\xi\eta$-plane, the orbital plane, given by

$$x = l_1\xi + l_2\eta, \qquad y = m_1\xi + m_2\eta, \qquad z = n_1\xi + n_2\eta.$$

$$\frac{dx}{dt} = l_1\left(\cos\theta\frac{dr}{dt} - r\sin\theta\frac{d\theta}{dt}\right) + l_2\left(\sin\theta\frac{dr}{dt} + r\cos\theta\frac{d\theta}{dt}\right),$$

with similar expressions for $\frac{dy}{dt}$ and $\frac{dz}{dt}$.

$$\frac{dx}{dt} = \frac{\mu}{H}[-l_1\sin\theta + l_2(e+\cos\theta)],$$

$$\frac{dy}{dt} = \frac{\mu}{H}[-m_1\sin\theta + m_2(e+\cos\theta)],$$

$$\frac{dz}{dt} = \frac{\mu}{H}[-n_1\sin\theta + n_2(e+\cos\theta)].$$

JACOBIAN

The area of a cross section in the xy-plane may not be exactly the same as the area of a cross section in the uv-plane. We want to determine the relationship; that is, we want to determine the scaling factor that is needed so that the areas are equal.

$$X=FK(\theta)$$