LECTURE NOTES

ON

SATELLITE COMMUNICATION

IV B. Tech II semester (MRCET-R13)

Ms. M. H Bindu Reddy
Assistant Professor

ELECTRONICS AND COMMUNICATION ENGINEERING

MALLA REDDY COLLEGE OF ENGINEERING & TECHNOLOGY
(Autonomous Institution – UGC, Govt. of India)
Sponsored by CMR Educational Society
(Affiliated to JNTU, Hyderabad, Approved by AICTE - Accredited by NBA & NAAC – 'A' Grade - ISO 9001:2008 Certified)
Maisammaguda, Dhulapally (Post Via Hakimpet), Secunderabad – 500100, Telangana State, India.
Contact Number: 040-23792146/64634237, E-Mail ID: mrcet2004@gmail.com, website: www.mrcet.ac.in

syllabus.

Course Objectives

- To prepare students to excel in basic knowledge of satellite communication principles
- To provide students with solid foundation in orbital mechanics and launches for the satellite communication
- To train the students with a basic knowledge of link design of satellite with a design examples.
- To provide better understanding of multiple access systems and earth station technology
- To prepare students with knowledge in satellite navigation and GPS & and satellite packet communications

UNIT -I

Communication Satellite: Orbit and Description: A Brief history of satellite Communication, Satellite Frequency Bands, Satellite Systems, Applications, Orbital Period and Velocity, effects of Orbital Inclination, Azimuth and Elevation, Coverage angle and slant Range, Eclipse, Orbital Perturbations, Placement of a Satellite in a Geo-Stationary orbit.

UNIT -II

Satellite Sub-Systems: Attitude and Orbit Control system, I I &C subsystem, Attitude Control subsystem, Power systems, Communication subsystems, Satellite Antenna Equipment.

Satellite Link: Basic Transmission Theory, System Noise Temperature and G/T ratio, Basic Link Analysis, Interference Analysis, Design of satellite Links for a specified C/N, (With and without frequency Re-use), Link Budget.

UNIT -III

Propagation effects: Introduction, Atmospheric Absorption, Cloud Attenuation, Tropospheric and lonospeheric Scintillation and Low angle fading, Rain induced attenuation, rain induced cross polarization interference.

Multiple Access: Frequency DivisIon Multiple Access (FDMA) – Intermodujation Calculation of C/N, Time Division Multiple Access (TDMA) – Frame Structure, Burst Structure, Satellite Switched TDMA, On-board Processing, Demand Assignment Multiple Access (DAMA) — Types of Demand Assignment, Characteristics, CDMA Spread Spectrum Transmission and Reception.

UNIT -IV

Earth Station Technology: Transmitters, Receivers, Antennas, Tracking Systems, Terrestrial Interface, Power Test Methods, Lower Orbit Considerations.

Satellite Navigation and Global POItIlg Systems: Radio and Satellite Navigation, GPS Position Location Principles, GPS Receivers, GPS C/A Code Accuracy, Differential GPS.

UNIT -V

Satellite Packet Communications: Message Transmission by FDMA: MI G/i Queue, Message Transmission by TDMA, PURE ALOHA-Satellite Packet Switching, Slotted Aloha, Packet Reservation, Tree Algorithm.

TEXT BOOKS

- Satellite Communications —Timothy Pratt, Charles Bostian, Jeremy Allnutt, 2nd Edition, 2003, John Wiley & Sons.
- Satellite Communications Engineering — Wilbur, L. Pritchand, Robert A. Nelson and Heuri G. Suyderhoud, 2nd Ed., Pearson Publications.
- Digital Satellite Communjcatjons..Trj–Ha 2nd Edition, 1990, Mc.Graw Hill.

REFERENCE BOOKS

- Satellite Communications Dennjs Roddy, 2nd Edition, 1996, McGraw Hill.
- Satellite Communications: Design Principles — M. Richcharia, 2nd Ed., BSP, 2003.
- Digital Satellite Communications — Tn. T. Ha, 2nd Ed., MGH, 1990.
- Fundamentals of Satellite Communications — K. N. Raja Rao, PHI, 2004.Course Outcomes

UNIT-1

COMMUNICATION SATELLITE

ORIGIN OF SATELLITE COMMUNICATIONS

The outer space has always fascinated people on the earth and communication through space evolved as an offshoot of ideas for space travel. The earliest idea of using artificial satellites for communications is found in a science fiction **Brick Moon** by Edward Evert Hale, published in 1869-70. While the early fictional accounts of satellite and space communications bear little resemblance to the technology as it exists today, they are of significance since they represent the origins of the idea from which the technology eventually evolved. In the area of satellite communications, the technology has been responsive to the imaginative dreams. Hence it is also expected that technological innovations will lead the evolution of satellite communications towards the visions of today.

Concept of Satellite Communications

Scientists from different countries conceived various ideas for communications through space along with the technological breakthroughs in different fields of science. The Russian scientist Konstantin Tsiolkovsky (1857-1935) was the first person to study space travel as a science and in 1879 formulated his Rocket Equation, which is still used in the design of modern rockets. He also wrote the first theoretical description of a man- made satellite and noted the existence of a geosynchronous orbit. But he did not identify any practical applications of geosynchronous orbit. The noted German Scientist and rocket expert, Hermann Oberth, in 1923 proposed that the crews of orbiting rockets could communicate with remote regions on earth by signalling with mirrors. In 1928, Austrian Scientist Hermann Noordung suggested that the geostationary orbit might be a good location for manned space vehicle. Russian Scientists in 1937 suggested that television images could be relayed by bouncing them off the space vehicles. During 1942-1943, a series of articles by George O Smith were published in Astounding Science Fictions concerning an artificial planet, Venus Equilateral, which functioned as relay station between Venus and Earth Station when direct communication was blocked by Sun. However, Arthur C. Clarke, an electronic engineer and the well-known science fiction writer is generally credited with originating the modern concept of Satellite Communications.

In 1945, Clarke, in his article **`Extra Terrestrial Relays: Can Rocket Stations give Worldwide Radio Coverage?'** published in Wireless World outlined the basic technical considerations involved in the concept of satellite communications. Clarke proposed orbiting space stations, which could be provided with receiving and transmitting equipment and could act as a repeater to relay transmission between any two points of the hemisphere beneath. He calculated that at an orbital radius of 42,000 km. the space station's orbit would coincide with the earth's rotation on its axis and the space station would remain fixed as seen from any point on the earth. He also pointed out that three such synchronous stations located 120 degrees apart above the equator could provide worldwide communications coverage. The concept was later considered to be generating a billion dollar business in the area of communications. However, Clarke did not patent the most commercially viable idea of twentieth century as he thought satellites would not be technically and economically viable until the next century.

Realization of concept to reality:
In October 1957, the first artificial satellite **Sputnik -I** was launched by former Soviet Russia in the earth's orbit and in 1963 Clark's idea became a reality when the first geosynchronous satellite **SYNCOM** was successfully launched by NASA.

The realization of the concept of satellite communications from an idea to reality has been possible due to a large number of technological breakthroughs and practical realization of devices and systems, which took place during and after the World War II. The pressures of international military rivalry during cold war period were also able to a great extent to push scientific and technological research and development far faster than it would have been possible if applied for peaceful purposes.

The successful launching of communications satellite in earth's orbit was possible because of keen interests shown by specific groups of people along with the developments in diverse areas of science and technology. Some of these factors, which are considered important in the realization of satellite communications, are:

- Development of high power rocket technology and propulsion systems capable of delivering satellites in high altitude orbits
- Scientific and military interests in Space Research
- Development of Transistors and miniaturization of electronic circuitry.
- Development of Solar Cells for providing sustained energy source for the satellite.
- Development of high-speed computers for calculating and tracking orbits.
- Government support in large-scale financial commitment to Space Technology Development for Military, Scientific Experiments and Civilian Applications.
- International military rivalry among super powers.
- The psychological impact of Sputnik Challenge leading to long range program of scientific research and development undertaken by US.

Before the transformation of the concept of communications by satellite to blue print and subsequent development of the hardware took place it was necessary to make the scientific communities convinced about the technical feasibility of such a system. In US J.R. Pierce, of Bell Laboratories initiated this by promoting the idea of transoceanic satellite communications within the scientific and technical communities. In 1955 Pierce in a paper entitled Orbital Radio Relays proposed detailed technical plan for passive communications satellites, disregarding the feasibility of constructing and placing satellites in orbit. He proposed three types of repeaters.

- Spheres at low altitudes
- A plane reflector
- An active repeater in 24 Hr. orbit

Pierce concluded his paper with a request to the scientific community to develop rockets capable of launching communications satellite. Fortunately, scientific and military interest in rocketry after World War II contributed in the development of a number of rockets like Atlas, Jupiter and Thor rockets in US and different multistage rockets in former USSR that ultimately made the launching of satellites in orbit possible.

On Oct. 4, 1957, **Sputnik-1** was launched as part of Russia's program for International Geophysical Year. The launching of Sputnik marks the dawn of the space age and the world's introduction to artificial satellite. Mass of Sputnik was only 184 lbs. in an orbit of 560 miles above the earth. It carried two radio transmitters at 20.005 MHz and 40.002 MHz. However this space craft was far more than a scientific and technical achievement as it had a tremendous psychological and political impact particularly on United States resulting in a technological competition between United States and Russia, long term planning in Space Research and establishment of NASA.

Four months after the launch of Sputnik, US **Explorer-1** was launched in January 1958 by a Jupiter rocket and the space race between Russia and US began.

HISTORICAL BACKGROUND:

Category	Year	Activity	Person/Agency/ Country.
Geostationary concept	1945	Suggestion of Geostationary satellite communication feasibility.	A. Clark (U.K)
Moon Reflection	1946	Detection of Lunar Echo by Radar	J. Mofenson (U.S.A.)
	1954	Passive relaying of voice by moon reflection.	J.H. Trexler (U.S.A.)
	1960	Hawaii-Washington, D.C. Communication by Moon Reflection.	U.S.A. Navy.
Low altitude orbit.	1957	Observation of signals from Sputnik -1 Satellite.	U.S.S.R., Japan and others.
	1958	Tape-recorded voice transmission by Satellite SCORE.	U.S.A. Air Force.
	1960	Meteorological facsimile Trans mission by Satellite Tiros-1.	U.S.A. NASA
	1960	Passive relaying of telephone and television by Satellite Echo-1.	U.S.A. Army.
	1960	Delayed relaying of recorded voice by	U.S.A. Army.

		Satellite Courier-1B.	
	1962	Active transatlantic relaying of communication by Satellite Telstar-1.	U.S.A., U.K., France.
	1962	Communication between manned Satellites Vostok-3 and 4; Space television transmission.	U.S.S.R.
	1963	Scatter communication by tiny needles in Orbit. (West Ford Project 6)	U.S.A. MIT.
	1963	Active transpacific relaying of communication by Satellite Relay 1.	U.S.A. NASA, Japan.
Synchronous Satellite.	1963	USA-Europe-Africa communication by Satellite Syncom 2.	U.S.A. NASA
	1964	Olympic Games television relaying by Satellite Syncom 3	U.S.A., NASA Japan.
	1965	Commercial Communication (Semi-experimental) by Satellite Early Bird.	INTELSAT.

BASIC CONCEPTS OF SATELLITE COMMUNICATIONS

- A communication satellite is an orbiting artificial earth satellite that receives a communications signal from a transmitting ground station, amplifies and possibly processes it, then transmits it back to the earth for reception by one or more receiving ground stations.

- Communications information neither originates nor terminates at the satellite itself. The satellite is an active transmission relay, similar in function to relay towers used in terrestrial microwave communications.

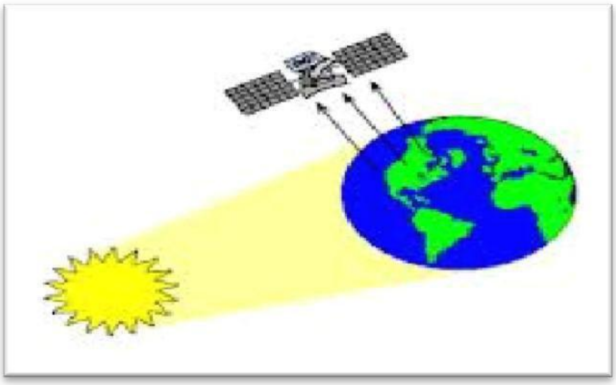
- The commercial satellite communications industry has its beginnings in the mid-1960s, and in less than 50 years has progressed from an alternative exotic technology to a mainstream transmission technology, which is pervasive in all elements of the global telecommunications infrastructure. Today's communications satellites offer extensive capabilities in applications involving data, voice, and video, with services provided to fixed, broadcast, mobile, personal communications, and private networks users.

Evolution of Satellite Communication:

- During early 1950s, both passive and active satellites were considered for the purpose of communications over a large distance.
- Passive satellites though successfully used in the early years of satellite communications, with the advancement in technology active satellites have completely replaced the passive satellites.

Passive Satellites:

- A satellite that only reflects signals from one Earth station to another or from several Earth stations to several others.
- It reflects the incident electromagnetic radiation without any modification or amplification.
- It can't generate power, they simply reflect the incident power.
- The first artificial passive satellite Echo-I of NASA was launched in August 1960.

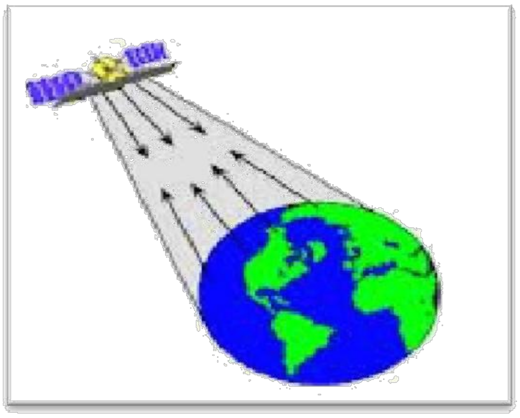


Disadvantages:

- Earth Stations required high power to transmit signals.
- Large Earth Stations with tracking facilities were expensive.
- A global system would have required a large number of passive satellites accessed randomly by different users.
- Control of satellites not possible from ground.
- The large attenuation of the signal while traveling the large distance between the transmitter and the receiver via the satellite was one of the most serious problems.

Active Satellites:

- In active satellites, it amplifies or modifies and retransmits the signal received from the earth.
- Satellites which can transmit power are called active satellite.
- Have several advantages over the passive satellites.
- Require lower power earth station.
- Not open to random use.
- Directly controlled by operators from ground.

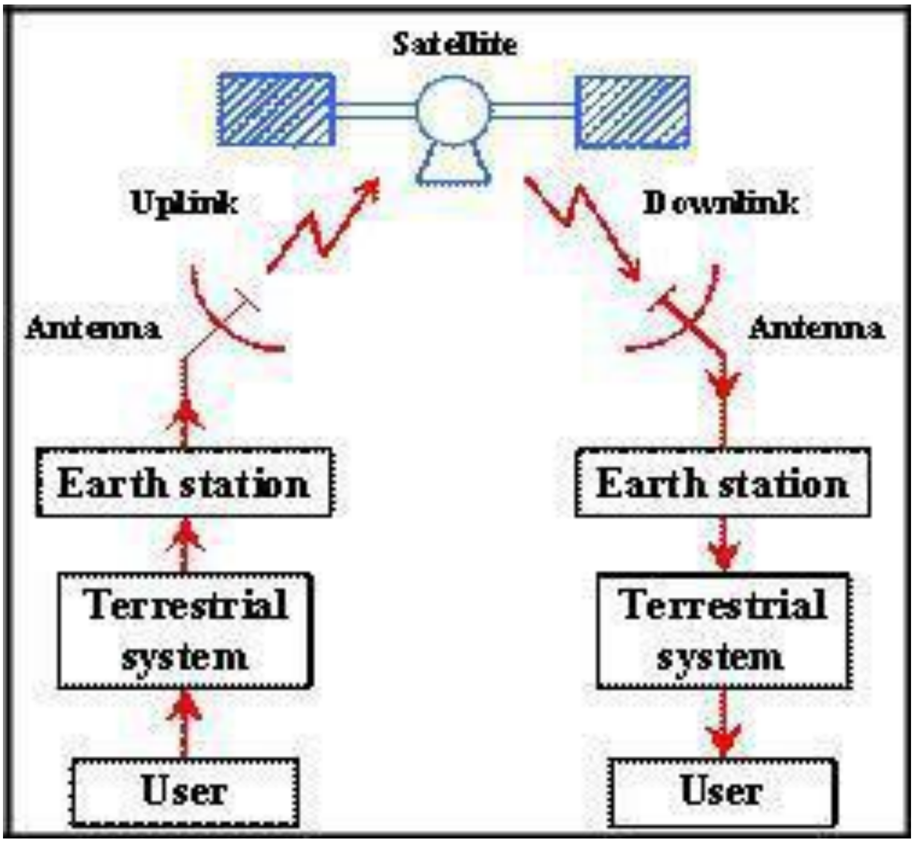


Disadvantages:

- Requirement of larger and powerful rockets to launch heavier satellites in orbit.
- Requirement of on-board power supply.
- Interruption of service due to failure of electronics components

Two major elements of Satellite Communications Systems are:

The satellite communications portion is broken down into two areas or segments: the ***space segment*** and the ***ground (or earth) segment***.



General architecture of Satellite Communication

Space Segment:

The elements of the space segment of a communications satellite system are shown in Figure. The space segment includes the satellite (or satellites) in orbit in the system, and the ground station that provides the operational control of the satellite(s) in orbit. The ground station is variously referred to as the ***Tracking, Telemetry, Command (TT&C)*** or the ***Tracking, Telemetry, Command and Monitoring (TTC&M)*** station. The TTC&M station provides essential spacecraft management and control functions to keep the satellite operating safely in orbit. The TTC&M links between the spacecraft and the ground are usually separate from the user communications links. TTC&M links may operate in the same frequency bands or in other bands. TTC&M is most often accomplished through a separate earth terminal facility specifically designed for the complex operations required to maintain a spacecraft in orbit.

Ground segment:

The ground segment of the communications satellite system consists of the earth surface area based terminals that utilize the communications capabilities of the Space Segment. TTC&M ground stations are ***not*** included in the ground segment. The ground segment terminals consist of three basic types:

- fixed (in-place) terminals;
- transportable terminals;
- mobile terminals.

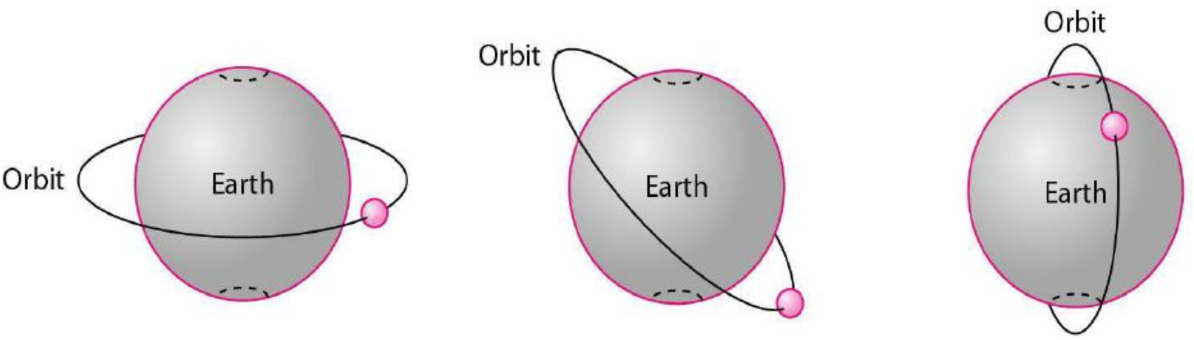
Fixed terminals are designed to access the satellite while fixed in-place on the ground. They may be providing different types of services, but they are defined by the fact that they are not moving while communicating with the satellite. Examples of fixed terminals are small terminals used in private networks (VSATs), or terminals mounted on residence buildings used to receive broadcast satellite signals. Transportable terminals are designed to be movable, but once on location remain fixed during transmissions to the satellite. Examples of the transportable terminal are satellite news gathering (SGN) trucks, which move to locations, stop in place, and then deploy an antenna to establish links to the satellite.

Mobile terminals are designed to communicate with the satellite while in motion. They are further defined as land mobile, aeronautical mobile, or maritime mobile, depending on their locations on or near the earth surface.

Satellite Control Centre function:

- Tracking of the satellite
- Receiving data
- Eclipse management of satellite
- Commanding the Satellite for station keeping.
- Determining Orbital parameters from Tracking and Ranging data
- Switching ON/OFF of different subsystems as per the operational requirements

SATELLITE ORBITS



a. Equatorial-orbit satellite b. Inclined-orbit satellite c. Polar-orbit satellite

Orbit: The path a Satellite follows around a planet is defined as an orbit.

- Satellite Orbits are classified in two broad categories :
  - Non-Geostationary Orbit (NGSO)
  - Geo Stationary Orbit (GSO)

- Early ventures with satellite communications used satellites in Non-geostationary low earth orbits due to the technical limitations of the launch vehicles in placing satellites in higher orbits.

Disadvantages of NGSO

- Complex problem of transferring signal from one satellite to another.
- Less expected life of satellites at NGSO.
- Requires frequent replacement of satellites compared to satellite in GSO

Geo Stationary Orbit (GSO)

- There is only one geostationary orbit possible around the earth
- Lying on the earth's equatorial plane.
- The satellite orbiting at the same speed as the rotational speed of the earth on its axis.

Advantages:

- Simple ground station tracking.
- Nearly constant range
- Very small frequency shift

Disadvantages:

- Transmission delay of the order of 250 msec.
- Large free space loss
- No polar coverage

Note: A geostationary orbit is a type of geosynchronous orbit. A geosynchronous orbit can be any orbit, like with an elliptical path, that has a period equal to the Earth's rotational period, whereas a geostationary orbit has to be a circular orbit and that too placed above the equator.

Satellite orbits in terms of the orbital height:

- According to distance from earth:
  - Geosynchronous Earth Orbit (GEO)
  - Medium Earth Orbit (MEO)
  - Low Earth Orbit (LEO)

Geostationary or geosynchronous earth orbit (GEO)

GEO satellites are synchronous with respect to earth. Looking from a fixed point from Earth, these satellites appear to be stationary. These satellites are placed in the space in such a way that only three satellites are sufficient to provide connection throughout the surface of the Earth (that is; their footprint is covering almost 1/3rd of the Earth). The orbit of these satellites is circular.

There are three conditions which lead to geostationary satellites. Lifetime expectancy of these satellites is 15 years.

1) The satellite should be placed 35,786 kms (approximated to 36,000 kms) above the surface of the earth.

2) These satellites must travel in the rotational speed of earth, and in the direction of motion of earth, that is eastward.

3) The inclination of satellite with respect to earth must be 0^0.

Geostationary satellite in practical is termed as geosynchronous as there are multiple factors which make these satellites shift from the ideal geostationary condition.

1) Gravitational pull of sun and moon makes these satellites deviate from their orbit. Over the period of time, they go through a drag. (Earth's gravitational force has no effect on these satellites due to their distance from the surface of the Earth.)

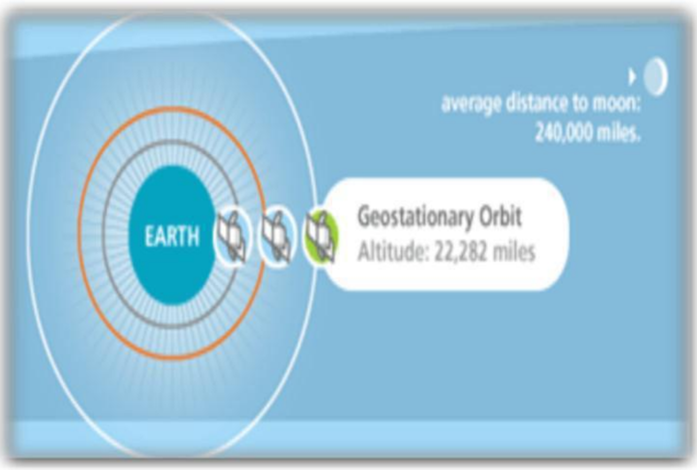
2) These satellites experience the centrifugal force due to the rotation of Earth, making them deviate from their orbit.

3) The non-circular shape of the earth leads to continuous adjustment of speed of satellite from the earth station.

These satellites are used for TV and radio broadcast, weather forecast and also, these satellites are operating as backbones for the telephone networks.

Disadvantages of GEO: Northern or southern regions of the Earth (poles) have more problems receiving these satellites due to the low elevation above a latitude of 60°, i.e., larger antennas are needed in this case. Shading of the signals is seen in cities due to high buildings and the low elevation further away from the equator limit transmission quality. The transmit power needed is relatively high which causes problems for battery powered devices. These satellites cannot be used for small mobile phones. The biggest problem for voice and also data communication is the high latency as without having any handovers, the signal has to at least travel 72,000 kms. Due to the large footprint, either frequencies cannot be reused or the GEO satellite needs special antennas focusing on a smaller footprint. Transferring a GEO into orbit is very expensive.

GEO: 35,786 km above the earth



Advantages Of GEO

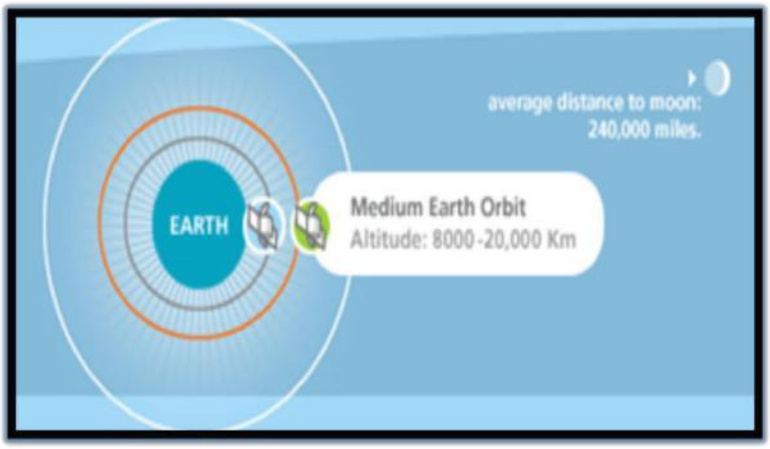
- Minimal Doppler shift
- These factors make it ideal for satellite broadcast and other multipoint applications
- GEO satellites have a 24 hour view of a particular area.
- A GEO satellite's distance from earth gives it a large coverage area, almost a fourth of the earth's surface.

Medium Earth Orbit (MEO) satellites:

MEOs can be positioned somewhere between LEOs and GEOs, both in terms of their orbit and due to their advantages and disadvantages. Using orbits around 20,000 km, the system only requires a dozen satellites which is more than a GEO system, but much less than a LEO system. These satellites move more slowly relative to the earth's rotation allowing a simpler system design (satellite periods are about six hours). Depending on the inclination, a MEO can cover larger populations, so requiring fewer handovers.

Disadvantages: Again, due to the larger distance to the earth, delay increases to about 70–80 ms. the satellites need higher transmit power and special antennas for smaller footprints.

MEO: 8,000-20,000 km above the earth



Advantages Of MEO

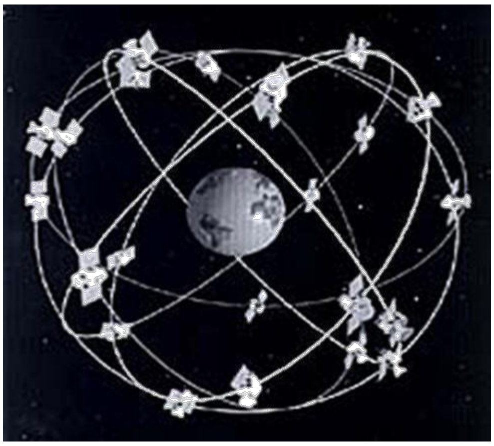
- A MEO satellite's longer duration of visibility and wider footprint means fewer satellites are needed in a MEO network than a LEO network.

Disadvantages Of MEO

- A MEO satellite's distance gives it a longer time delay and weaker signal than a LEO satellite, though not as bad as a GEO satellite.

MEO satellites

The GPS constellation calls for 24 satellites to be distributed equally among six circular orbital planes



GPS Constellation

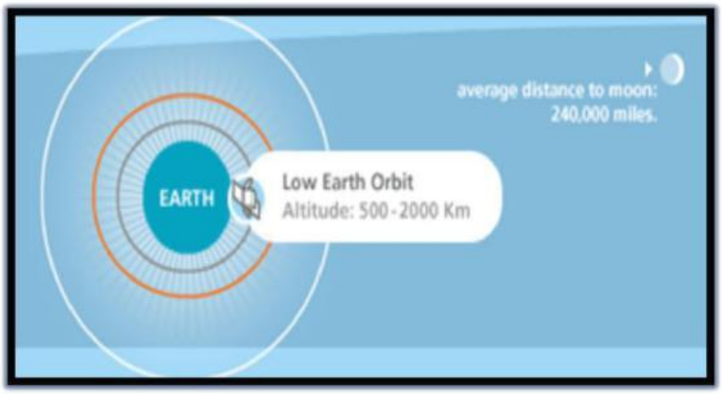
Low Earth Orbit (LEO) satellites:
These satellites are placed 500-1500 kms above the surface of the earth. As LEOs circulate on a lower orbit, hence they exhibit a much shorter period that is 95 to 120 minutes. LEO systems try to ensure a high elevation for every spot on earth to provide a high quality communication link. Each LEO satellite will only be visible from the earth for around ten minutes.

Using advanced compression schemes, transmission rates of about 2,400 bit/s can be enough for voice communication. LEOs even provide this bandwidth for mobile terminals with Omni-directional antennas using low transmit power in the range of 1W. The delay for packets delivered via a LEO is relatively low (approx 10 ms). The delay is comparable to long-distance wired connections (about 5–10 ms). Smaller footprints of LEOs allow for better frequency reuse, similar to the concepts used for cellular networks. LEOs can provide a much higher elevation in Polar Regions and so better global coverage.

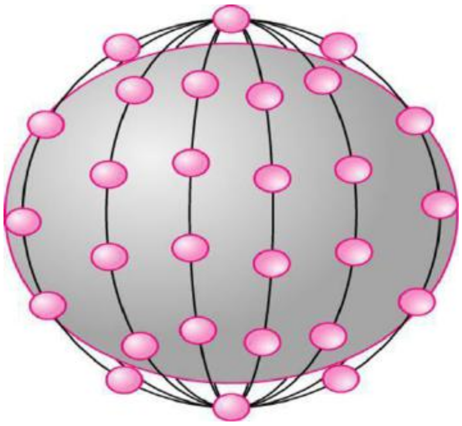
These satellites are mainly used in remote sensing an providing mobile communication services (due to lower latency).

Disadvantages: The biggest problem of the LEO concept is the need for many satellites if global coverage is to be reached. Several concepts involve 50–200 or even more satellites in orbit. The short time of visibility with a high elevation requires additional mechanisms for connection handover between different satellites. The high number of satellites combined with the fast movements resulting in a high complexity of the whole satellite system. One general problem of LEOs is the short lifetime of about five to eight years due to atmospheric drag and radiation from the inner Van Allen belt1. Assuming 48 satellites and a lifetime of eight years, a new satellite would be needed every two months. The low latency via a single LEO is only half of the story. Other factors are the need for routing of data packets from satellite to if a user wants to communicate around the world. Due to the large footprint, a GEO typically does not need this type of routing, as senders and receivers are most likely in the same footprint.

LEO: 500-2,000 km above the earth



The Iridium system shown below has 66 satellites in six LEO orbits, each at an altitude of 750 km.



Iridium is designed to provide direct worldwide voice and data communication using handheld terminals, a service similar to cellular telephony but on a global scale.

Advantages Of LEO

- A LEO satellite's proximity to earth compared to a GEO satellite gives it a better signal strength and less of a time delay, which makes it better for point to point communication.
- A LEO satellite's smaller area of coverage is less and waste of bandwidth.

Disadvantages Of LEO

- A network of LEO satellites is needed, which can be costly
- LEO satellites have to compensate for Doppler shifts cause by their relative movement.
- Atmospheric drag effects LEO satellites, causing gradual orbital deterioration.

Advantages Of Satellite Communication

- **Universal:** Satellite communications are available virtually everywhere.
- **Versatile:** Satellites can support all of today's communications needs.
- **Reliable:** Satellite is a proven medium for supporting a company's communications needs.
- **Seamless:** Satellite's inherent strength as a broadcast medium makes it perfect.
- **Fast:** Since satellite networks can be set up quickly, companies can be fast-to-market with new services.
- Flexible
- Expandable
- High Quality
- Quick Provision of Services
- Mobile and Emergency Communication
- Suitable for both Digital and Analog Transmission

FREQUENCY ALLOCATIONS FOR SATELLITE SERVICES

Allocation of frequencies to satellite services s a complicated process which requires international coordination and planning. This is done as per the International Telecommunication Union (ITU). To implement this frequency planning, the world is divided into three regions:

Region1: Europe, Africa and Mongolia
Region 2: North and South America and Greenland
Region 3: Asia (excluding region 1 areas), Australia and south-west Pacific.

Within these regions, he frequency bands are allocated to various satellite services. Some of them are listed below.

- **Fixed satellite service**: Provides Links for existing Telephone Networks Used for transmitting television signals to cable companies
- **Broadcasting satellite service**: Provides Direct Broadcast to homes. E.g. Live Cricket matches etc
- **Mobile satellite service**s: This includes services for: Land Mobile Maritime Mobile Aeronautical mobile
- **Navigational satellite services** : Include Global Positioning systems
- **Meteorological satellite services**: They are often used to perform Search and Rescue service

Below are the frequencies allocated to these satellites:
Frequency Band (GHZ) Designations:
VHF: 01-0.3
UHF: 0.3-1.0
L-band: 1.0-2.0
S-band: 2.0-4.0
C-band: 4.0-8.0
X-band: 8.0-12.0
Ku-band: 12.0-18.0 (Ku is Under K Band)
Ka-band: 18.0-27.0 (Ka is Above K Band)
V-band: 40.0-75.0
W-band: 75-110
Mm-band: 110-300
μm-band: 300-3000
Based on the satellite service, following are the frequencies allocated to the satellites:

Frequency Band (GHZ) Designations:

VHF: 01-0.3 ---Mobile & Navigational Satellite Services
L-band: 1.0-2.0 --- Mobile & Navigational Satellite Services
C-band: 4.0-8.0 --- Fixed Satellite Service
Ku-band: 12.0-18.0 --- Direct Broadcast Satellite Services

Band	Frequency Range	Total Bandwidth	General Application
L	1 to 2 GHz	1 GHz	Mobile satellite service (MSS)
S	2 to 4 GHz	2 GHz	MSS, NASA, deep space research
C	4 to 8 GHz	4 GHz	Fixed satellite service (FSS)
X	8 to 12.5 GHz	4.5 GHz	FSS military, terrestrial earth exploration, and meteorological satellites
Ku	12.5 to 18 GHz	5.5 GHz	FSS, broadcast satellite service (BSS)
K	18 to 26.5 GHz	8.5 GHz	BSS, FSS
Ka	26.5 to 40 GHz	13.5 GHz	FSS

APPLICATIONS OF SATELLITE COMMUNICATION

1) Weather Forecasting: Certain satellites are specifically designed to monitor the climatic conditions of earth. They continuously monitor the assigned areas of earth and predict the weather conditions of that region. This is done by taking images of earth from the satellite. These images are transferred using assigned radio frequency to the earth station. (Earth Station: it's a radio station located on the earth and used for relaying signals from satellites.) These satellites are exceptionally useful in predicting disasters like hurricanes, and monitor the changes in the Earth's vegetation, sea state, ocean color, and ice fields.

2) Radio and TV Broadcast: These dedicated satellites are responsible for making 100s of channels across the globe available for everyone. They are also responsible for broadcasting live matches, news, world-wide radio services. These satellites require a 30-40 cm sized dish to make these channels available globally.

3) Military Satellites: These satellites are often used for gathering intelligence, as a communications satellite used for military purposes, or as a military weapon. A satellite by itself is neither military nor civil. It is the kind of payload it carries that enables one to arrive at a decision regarding its military or civilian character.

4) Navigation Satellites: The system allows for precise localization world-wide, and with some additional techniques, the precision is in the range of some meters. Ships and aircraft rely on GPS as an addition to traditional navigation systems. Many vehicles come with installed GPS receivers. This system is also used, e.g., for fleet management of trucks or for vehicle localization in case of theft.

5) Global Telephone: One of the first applications of satellites for communication was the establishment of international telephone backbones. Instead of using cables it was sometimes faster to launch a new satellite. But, fiber optic cables are still replacing satellite communication across long distance as in fiber optic cable, light is used instead of radio frequency, hence making the communication much faster (and of course, reducing the delay caused due to the amount of distance a signal needs to travel before reaching the destination.). Using satellites, to typically reach a distance approximately 10,000 kms away, the signal needs to travel almost 72,000 kms, that is, sending data from ground to satellite and (mostly) from satellite to another location on earth. This cause's substantial amount of delay and this delay becomes more prominent for users during voice calls.

6) Connecting Remote Areas: Due to their geographical location many places all over the world do not have direct wired connection to the telephone network or the internet (e.g., researchers on Antarctica) or because of the current state of the infrastructure of a country. Here the satellite provides a complete coverage and (generally) there is one satellite always present across a horizon.

7) Global Mobile Communication: The basic purpose of satellites for mobile communication is to extend the area of coverage. Cellular phone systems, such as AMPS and GSM (and their successors) do not cover all parts of a country. Areas that are not covered usually have low population where it is too expensive to install a base station. With the integration of satellite communication, however, the mobile phone can switch to satellites offering world-wide connectivity to a customer. Satellites cover a certain area on the earth.

This area is termed as a „footprint" of that satellite. Within the footprint, communication with that satellite is possible for mobile users. These users communicate using a Mobile-User-Link (MUL). The base-stations communicate with satellites using a Gateway-Link (GWL). Sometimes it becomes necessary for satellite to create a communication link between users belonging to two different footprints. Here the satellites send signals to each other and this is done using Inter-Satellite-Link (ISL).

FUTURE OF SATELLITE COMMUNICATIONS

Future communication satellites will have

- More onboard processing capabilities,
- More power, and
- Larger-aperture antennas that will enable satellites to handle more bandwidth.
- The demand for more bandwidth will ensure the long-term viability of the commercial satellite industry well into the 21st century.

Conclusion:

By going through the above slides we came to know that satellite is mostly responsible for:

- Telecommunication transmission
- Reception of television signals
- Whether forecasting

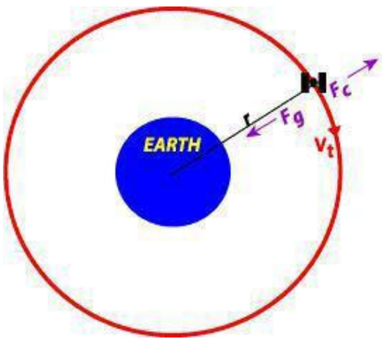
Which are very important in our daily life.

ORBITAL MECHANICS AND LAUNCHERS

ORBITAL MECHANICS

- To achieve a stable orbit around the earth, a spacecraft must first be beyond the bulk of the earth's atmosphere, i.e., in what is popularly called space.
- According to Newton's law of motion F=ma. Where a = acceleration, F= force acting on the object and m= mass of the object. It helps us understand the motion of satellite in a stable orbit.(neglecting any drag or other perturbing forces).
- (F=ma) states that the force acting on a body is equal to the mass of the body multiplied by the resulting acceleration of the body.
- Thus, for a given force, the lighter the mass of the body, the higher the acceleration will be.
- When in a stable orbit, there are two main forces acting on a satellite: a centrifugal force due to the kinetic energy of the satellite, which attempts to fling the satellite into a higher orbit, and a centripetal force due to gravitational attraction of the planet about which the satellite is orbiting, which attempts to pull the satellite towards the planet.
- If these two forces are equal the satellite remains in a stable orbit.

Forces involved in orbital mechanics



There are two relevant forces involved in this problem

1.Gravitational force= attraction between any two objects, given by

2.Centrifugal force=an outward-directed force that normally balances the inward-directed centripetal force

The standard acceleration due to gravity at the earth surface is 981 cm/s^2. The value decreases with height above the earth's surface. The acceleration, a, due to gravity at a distance r from the centre of the earth is

$$a=\mu/r^2 \ km/s^2$$

Where the constant μ is the product of the universal gravitational constant G and the mass of the earth M_E.

The product GM_E is called kepler's constant and has the value 3.98 x 10^5 km^3/s^2.
The universal gravitational constant is G=6.672x 10^{-11} Nm^2/kg^2.

The mass of the earth $M_E = 5.97 \times 10^{24}$ kg.

Since fore= mass x acceleration, the centripetal force acting on the satellite, Fin is given by

$$\mathbf{Fin = m \times (\mu/r^2)}$$

$$\mathbf{= m \times (G\ M_E / r^2)}$$

In a similar fashion, the centrifugal acceleration is given by

$$\mathbf{a = v^2 / r}$$

Which will give the centrifugal force, Fout as

$$\mathbf{Fout = m \times (v^2 / r)}$$

If the forces of the satellite are balanced **Fin=Fout**

$$\mathbf{m \times (\mu/r^2) = m \times (v^2 / r)}$$

Hence the velocity v of the satellite in a circular orbit is given by

$$\mathbf{v = (\mu/r)^{1/2}}$$

If the orbit is circular, the distance traveled by a satellite in one orbit around a planet is $2\prod r$, where r is the radius of the orbit from the satellite to the center of the planet. Since distance divided by velocity equals time to travel the distance, the period of satellite's orbit, T, will be

$$\mathbf{T = (2\prod r)/v = (2\prod r)/[(\mu/r)^{1/2}]}$$

$$\mathbf{T = (2\prod r^{3/2})/(\mu^{1/2})}$$

Using standard mathematical procedures we can develop an equation for the radius of the satellite's orbit, r, namely

Kepler's Laws

Kepler's laws of planetary motion apply to any two bodies in space that interact through gravitation. The laws of motion are described through three fundamental principles.

Kepler's First Law, as it applies to artificial satellite orbits, can be simply stated as follows: 'The path followed by a satellite around the earth will be an ellipse, with the center of mass of earth as one of the two foci of the ellipse.' This is shown in Figure:

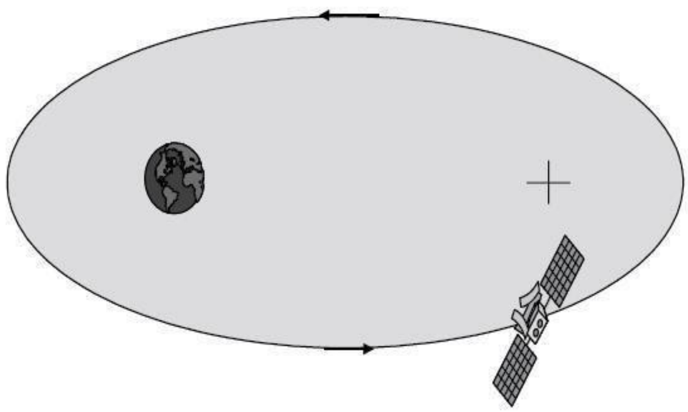


Figure Kepler's First Law

If no other forces are acting on the satellite, either intentionally by orbit control or unintentionally as in gravity forces from other bodies, the satellite will eventually settle in an elliptical orbit, with the earth as one of the foci of the ellipse. The 'size' of the ellipse will depend on satellite mass and its angular velocity.

Kepler's Second Law can likewise be simply stated as follows: 'for equal time intervals, the satellite sweeps out equal areas in the orbital plane.' Figure 2.3 demonstrates this concept.

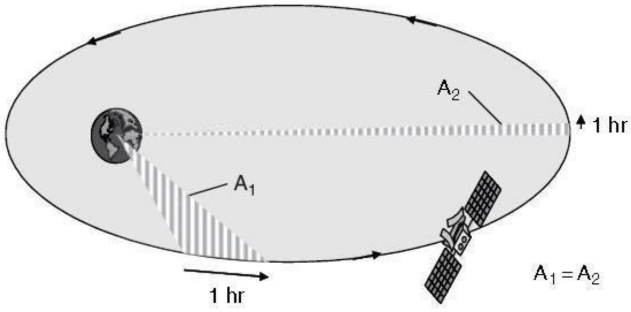


Figure 2.3 Kepler's Second Law

The shaded area A1 shows the area swept out in the orbital plane by the orbiting satellite in a one hour time period at a location near the earth. Kepler's second law states that the area swept out by any other one hour time period in the orbit will also sweep out an area equal to A1. For example, the area swept out by the satellite in a one hour period around the point farthest from the earth (the orbit's apogee), labeled A2 on the figure, will be equal to A1, i.e.: A1 =A2.
This result also shows that the satellite orbital velocity is not constant; the satellite is moving much faster at locations near the earth, and slows down as it approaches apogee. This factor will be discussed in more detail later when specific satellite orbit types are introduced.

Kepler's Third Law is as follows: 'the square of the periodic time of orbit is proportional to the cube of the mean distance between the two bodies.' This is quantified as follows:

$$T^2 = \left[\frac{4\pi^2}{\mu}\right] a^3$$

Where T=orbital period in s; a=distance between the two bodies, in km;
μ=Kepler's Constant =3.986004×105 km3/s2. If the orbit is circular,
then a=r, and

$$r = \left[\frac{\mu}{4\,\pi^2}\right]^{\frac{1}{3}} T^{\frac{2}{3}}$$

This demonstrates an important result: Orbit Radius = [Constant] × (Orbit Period)$^{2/3}$

Under this condition, a specific orbit period is determined only by proper selection of the orbit radius. This allows the satellite designer to select orbit periods that best meet particular application requirements by locating the satellite at the proper orbit altitude. The altitudes required to obtain a specific number of repeatable ground traces with a circular orbit are listed in Table 2.1.

Table 2.1 Orbit altitudes for specified orbital periods

Revolutions/day	Nominal period (hours)	Nominal altitude (km)
1	24	36000
2	12	20200
3	8	13900
4	6	10400
6	4	6400
8	3	4200

Orbital Elements:

Apogee: A point for a satellite farthest from the Earth. It is denoted as **ha.**

Perigee**:** A point for a satellite closest from the Earth. It is denoted as **hp.**

Line of Apsides: Line joining perigee and apogee through centre of the Earth. It is the major axis of the orbit. One-half of this line's length is the semi-major axis equivalents to satellite's mean distance from the Earth.

Ascending Node: The point where the orbit crosses the equatorial plane going from north to south.

Descending Node: The point where the orbit crosses the equatorial plane going from south to north.

Inclination: the angle between the orbital plane and the Earth's equatorial plane. Its measured at the ascending node from the equator to the orbit, going from East to North. Also, this angle is commonly denoted as **i.**

Line of Nodes: the line joining the ascending and descending nodes through the centre of Earth.

Prograde Orbit: an orbit in which satellite moves in the same direction as the Earth's rotation. Its inclination is always between 0^0 to 90^0. Many satellites follow this path as Earth's velocity makes it easier to lunch these satellites.

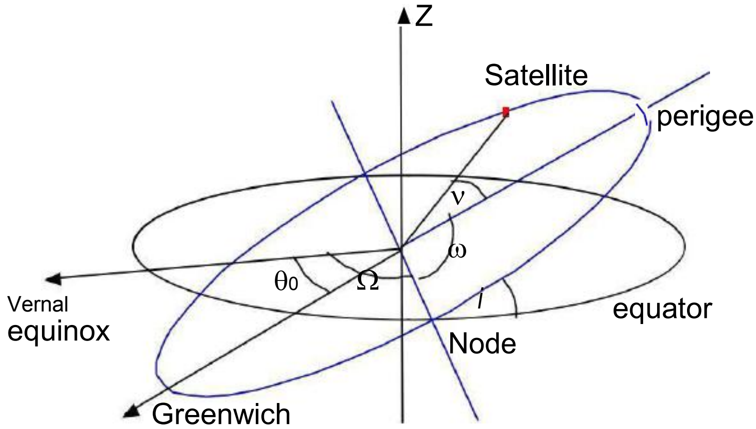
Retrograde Orbit: an orbit in which satellite moves in the same direction counter to the Earth's rotation.

Argument of Perigee: An angle from the point of perigee measure in the orbital plane at the Earth's centre, in the direction of the satellite motion.

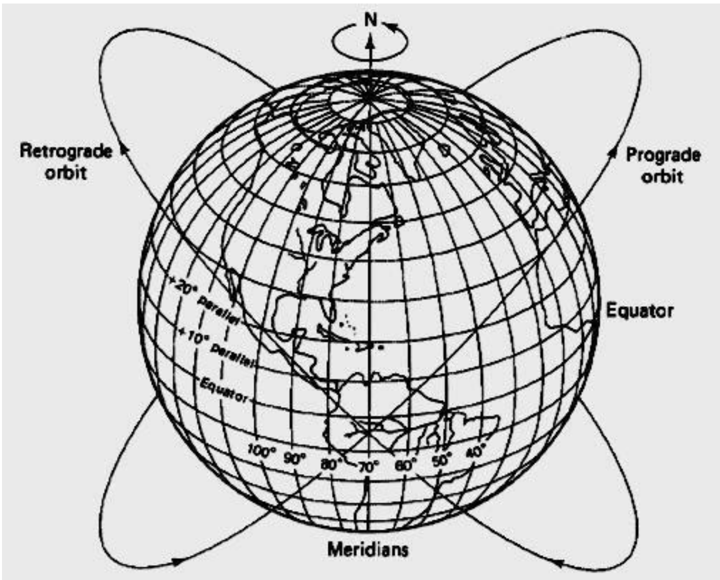
Right ascension of ascending node: The definition of an orbit in space, the position of ascending node is specified. But as the Earth spins, the longitude of ascending node changes and cannot be used for reference. Thus for practical determination of an orbit, the longitude and time of crossing the ascending node is used. For absolute measurement, a fixed reference point in space is required. It could also be defined as "*right ascension of the ascending node; right ascension is the angular position measured eastward along the celestial equator from the vernal equinox vector to the hour circle of the object*".

Mean anamoly: It gives the average value to the angular position of the satellite with reference to the perigee.

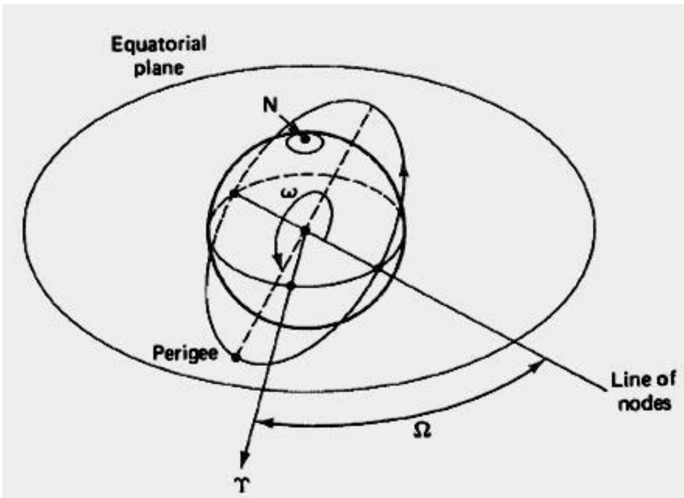
True anamoly: It is the angle from point of perigee to the satellite's position, measure at the Earth's centre.



i Inclination
Ω Right Ascension of ascending node ω Argument of perigee ν True anomaly



Prograde and Retrograde orbits



Argument of Perigee and Right ascension of ascending node

Orbital Elements Following are the 6 elements of the Keplerian Element set commonly known as orbital elements.

- Semi-Major axis (a)
- Eccentricity (e)

They give the shape (of ellipse) to the satellite's orbit.

3. Mean anomaly (M0)

It denotes the position of a satellite in its orbit at a given reference time.

4. Argument of Perigee

It gives the rotation of the orbit's perigee point relative to the orbit‟s nodes in the earth‟s equatorial plane.

- Inclination
- Right ascension of ascending node

They relate the orbital plane's position to the Earth. As the equatorial bulge causes a slow variation in argument of perigee and right ascension of ascending node, and because other perturbing forces may alter the orbital elements slightly, the values are specified for the reference time or epoch.

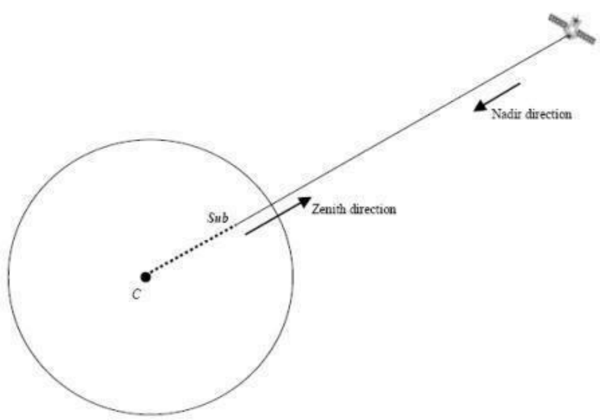
LOOK ANGLE DETERMINATION

The look angles for the ground station antenna are Azimuth and Elevation angles. They are required at the antenna so that it points directly at the satellite. Look angles are calculated by considering the elliptical orbit. These angles change in order to track the satellite.

For geostationary orbit, these angels values does not change as the satellites are stationary with respect to earth. Thus large earth stations are used for commercial communications, these antennas beamwidth is very narrow and the tracking mechanism is required to compensate for the movement of the satellite about the nominal geostationary position.

For home antennas, antenna beamwidth is quite broad and hence no tracking is essential. This leads to a fixed position for these antennas.

Sub satellite point: The point, on the earth's surface of intersection between a line frim the earth's center to the satellite.

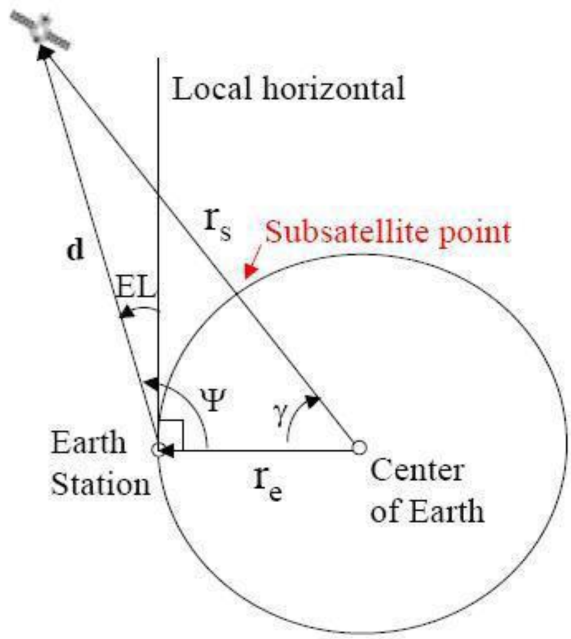


The following information is needed to determine the look angles of geostationary orbit.

- Earth Station Latitude
- Earth Station Longitude
- Sub-Satellite Point's Longitude
- ES: Position of Earth Station
- SS: Sub-Satellite Point
- S: Satellite
- Range from ES to S
- Angle to be determined

Geometry of Elevation Angle

- Plane in picture is the one that includes center of the earth, Earth Station and Satellite.
- Subsatellite point will also be on the same plane.



$El = \psi - 90^o$

γ = **central angle**

r_s = **radius to the satellite**

r_e = **radius of the earth**

Satellite Coordinates

- SUB-SATELLITE POINT
  - Latitude Ls
  - Longitude ls
- EARTH STATION LOCATION
  - Latitude Le
  - Longitude le

Calculate γ, Angle at earth center

Central Angle

γ is defined so that it is non-negative and

$$\cos(\gamma) = \cos(Le)\cos(L_s)\cos(l_s - l_e) + \sin(L_e)\sin(L_s)$$

The magnitude of the vectors joining the center of the earth, the satellite and the earth station are related by the law of cosine:

$$d = r_s\left[1+\left(\frac{r_e}{r_s}\right)^2 - 2\left(\frac{r_e}{r_s}\right)\cos(\gamma)\right]^{1/2}$$

Elevation Angle Calculation

By the sine law we have

$$\frac{r_s}{\sin(\psi)} = \frac{d}{\sin(\gamma)}$$

Which yields

$$\cos(El) = \frac{\sin(\gamma)}{\left[1+\left(\frac{r_e}{r_s}\right)^2 - 2\left(\frac{r_e}{r_s}\right)\cos(\gamma)\right]^{1/2}}$$

Azimuth Angle Calculation for GEO Satellites

- SUB-SATELLITE POINT
  - Equatorial plane, Latitude Ls = 0^0
  - Longitude ls
- EARTH STATION LOCATION
  - Latitude Le
  - Longitude le

The original calculation previously shown:

$$\cos(\gamma) = \cos(Le)\cos(L_s)\cos(l_s - l_e) + \sin(L_e)\sin(L_s)$$

Simplifies using $L_s = 0^o$ since the satellite is over the equator:

$$\boxed{\cos(\gamma) = \cos(Le)\cos(l_s - l_e)}$$

Step 2. Find the elevation angle El

$$\cos(El) = \frac{\sin(\gamma)}{\left[1.02288826 - 0.3025396\cos(\gamma)\right]^{1/2}}$$

To find the azimuth angle, an *intermediate angle*, α, must first be found. The intermediate angle allows the correct quadrant (see Figs. 2.10 & 2.13) to be found since the azimuthal direction can lie anywhere between 0° (true North) and clockwise through 360° (back to true North again). The intermediate angle is found from

$$\alpha = \tan^{-1}\left[\frac{\tan\left|(l_s - l_e)\right|}{\sin(L_e)}\right]$$

Case 1: Earth station in the Northern Hemisphere with
- (a) Satellite to the SE of the earth station: $Az = 180° - \alpha$
- (b) Satellite to the SW of the earth station: $Az = 180° + \alpha$

Case 2: Earth station in the Southern Hemisphere with
- (c) Satellite to the NE of the earth station: $Az = \alpha$
- (d) Satellite to the NW of the earth station: $Az = 360° - \alpha$

Example for Look Angle Calculation of a GEO satellite

FIND the **Elevation** and **Azimuth** Look Angles for the following case:

Earth Station Latitude	52° N	London, England
Earth Station Longitude	0°	Dockland region
Satellite Latitude	0°	Geostationary
Satellite Longitude	66° E	INTELSAT IOR Primary

Step 1. Find the central angle γ

$$\cos(\gamma) = \cos(L_e)\cos(l_s - l_e) = \cos(52)\cos(66) = 0.2504$$

yielding $\gamma = 75.4981°$

$$El = 5.85^{o}$$

Step 3. Find the intermediate angle, α

$$\alpha = \tan^{-1}\left[\frac{\tan\left|(l_s - l_e)\right|}{\sin(L_e)}\right]$$

$= \tan^{-1}$ [(tan (66 - 0)) / sin (52)]

= 70.6668

The earth station is in the Northern hemisphere and the satellite is to the South East of the earth station. This gives

$Az = 180^{o} - \alpha$

$= 180 - 70.6668 = 109.333^{o}$ (clockwise from true North)

ANSWER: The look-angles to the satellite are

Elevation Angle = 5.85°

Azimuth Angle = 109.33°

NOTE

- The earth station can see a satellite over a geostationary arc bounded by **+- (81.30)** about the earth station's longitude.

ORBITAL PERTURBATIONS

- Theoretically, an orbit described by Kepler is ideal as Earth is considered to be a perfect sphere and the force acting around the Earth is the centrifugal force. This force is supposed to balance the gravitational pull of the earth.

- In reality, other forces also play an important role and affect the motion of the satellite. These forces are the gravitational forces of Sun and Moon along with the atmospheric drag.

- Effect of Sun and Moon is more pronounced on geostationary earth satellites where as the atmospheric drag effect is more pronounced for low earth orbit satellites.

- As the shape of Earth is not a perfect sphere, it causes some variations in the path followed by the satellites around the primary. As the Earth is bulging from the equatorial belt, and keeping in mind that an orbit is not a physical entity, and it is the forces resulting from an oblate Earth which act on the satellite produce a change in the orbital parameters.

- This causes the satellite to drift as a result of regression of the nodes and the latitude of the point of perigee (point closest to the Earth). This leads to rotation of the line of apsides. As the orbit itself is moving with respect to the Earth, the resultant changes are seen in the values of argument of perigee and right ascension of ascending node.

- Due to the non-spherical shape of Earth, one more effect called as the "Satellite Graveyard" is seen. The non-spherical shape leads to the small value of eccentricity at the equatorial plane. This causes a gravity gradient on GEO satellite and makes them drift to one of the two stable points which coincide with minor axis of the equatorial ellipse.

- Working satellites are made to drift back to their position but out-of-service satellites are eventually drifted to these points, and making that point a Satellite Graveyard.

Atmospheric Drag

- For Low Earth orbiting satellites, the effect of atmospheric drag is more pronounces. The impact of this drag is maximum at the point of perigee. Drag (pull towards the Earth) has an effect on velocity of Satellite (velocity reduces).

- This causes the satellite to not reach the apogee height successive revolutions. This leads to a change in value of semi-major axis and eccentricity. Satellites in service are maneuvered by the earth station back to their original orbital position.

ORBIT DETERMINATION

Orbit determination requires that sufficient measurements be made to determine uniquely the six orbital elements needed to calculate the future of the satellite, and hence calculate the required changes that need to be made to the orbit to keep it within the nominal orbital location. The control earth stations used to measure the angular position of the satellites also carryout range measurements using unique time stamps in the telemetry stream or communication carrier. These earth stations generally referred to as the TTC&M(telemetry tracking command and monitoring) stations of the satellite network.

LAUNCHES AND LAUNCH VEHICLES

A satellite cannot be placed into a stable orbit unless two parameters that are uniquely coupled together the velocity vector and the orbital height are simultaneously correct. There is little point in orbiting the correct height and not having the appropriate velocity component in the correct direction to achieve the desired orbit. A geostationary satellite for example must be in an orbit at height 35,786.03km above the surface of the earth with an inclination of zero degrees an ellipticity of zero, and a velocity of 3074.7m/s tangential to the earth in the plane of the orbit, which is the earths equatorial plane. The further out from the earth the orbit is greater the energy required from the launch vehicle to reach that orbit. In any earth satellite launch, the largest fraction of the energy expanded by the rocket is used to accelerate the vehicle from rest until it is about 20miles (32 km) above the earth.

To make the most efficient use of the fuel, it is common to shed excess mass from the launcher as it moves upward on launch; this is called staging.

Most launch vehicles have multiple stage and as each stage is completed that portion of the launcher is expended until the final stage places the satellite into the desired trajectory. Hence the term:expandable lauch vehicle(ELV). The space shuttle , called the space transportation system (STS)by NASA, is partially reusable. The solid rocket boosters are recovered and refurbished for future mission and the shuttle vehicle itself is flown back to earth for refurbishment and reuse. Hence the term:reusable launch vehicle(RLV) for such launchers.

Vehicle	Ariane 5	Atlas V	Delta IV Medium	Dnepr M	Falcon 9	Proton M	Rockot	Soyuz 2	Zenit 3SL
Country	Europe	USA	USA	Russia	USA	Russia	Russia	Russia	Multinational
LEO kg (lbs)	17,250 (37,950)	9,800-29,400 (21,600-64,820)	8,120 (17,885)	4,100 (9,030)	10,450 (22,990)	21,000 (46,305)	1,850 (4,075)	7,800 (17,100)	15,246 (33.611)
GTO kg (lbs)	10,500 (23,127)	4,750-13,000 (10,470-28,660)	4,210 (9,273)	--	4,680 (10,296)	5,500 (12,125)	--	1,700 (3,800)	6,100 (13,448)

Launch vehicle selection factor

- Price/cost
- Reliability-Recent launch success/failure history
- Dependable launch schedule- Urgency of the customer
- Performance
- Spacecraft fit
- Safety issues
- Launch site location
- Availability-launch site; vehicle; schedule;
- Market conditions-what the market will bear

LAUNCHING ORBITS

Low Earth Orbiting satellites are directly injected into their orbits. This cannot be done incase of GEOs as they have to be positioned 36,000kms above the Earth"s surface. Launch vehicles are hence used to set these satellites in their orbits. These vehicles are reusable. They are also known as „Space Transportation System" (STS).

When the orbital altitude is greater than 1,200 km it becomes expensive to directly inject the satellite in its orbit. For this purpose, a satellite must be placed in to a transfer orbit between the initial lower orbit and destination orbit. The transfer orbit is commonly known as *Hohmann-Transfer Orbit.

(*About Hohmann Transfer Orbit: This manoeuvre is named for the German civil engineer who first proposed it, Walter Hohmann, who was born in 1880. He didn't work in rocketry professionally (and wasn't associated with military rocketry), but was a key member of Germany's pioneering Society for Space Travel that included people such as Willy Ley, Hermann, and Werner von Braun. He published his concept of how to transfer between orbits in his 1925 book, The Attainability of Celestial Bodies.)

The transfer orbit is selected to minimize the energy required for the transfer. This orbit forms a tangent to the low attitude orbit at the point of its perigee and tangent to high altitude orbit at the point of its apogee.

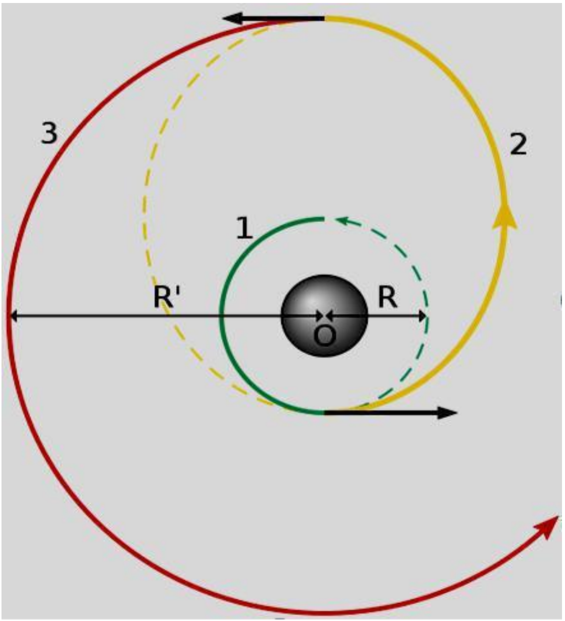


Figure: Orbit Transfer positions

The rocket injects the satellite with the required thrust** into the transfer orbit. With the STS, the satellite carries a perigee kick motor*** which imparts the required thrust to inject the satellite in its transfer orbit. Similarly, an apogee kick motor (AKM) is used to inject the satellite in its destination orbit.

Generally it takes 1-2 months for the satellite to become fully functional. The Earth Station performs the Telemetry Tracking and Command**** function to control the satellite transits and functionalities.

(**Thrust: It is a reaction force described quantitatively by Newton's second and third laws. When a system expels or accelerates mass in one direction the accelerated mass will cause a force of equal magnitude but opposite direction on that system.)
(***Kick Motor refers to a rocket motor that is regularly employed on artificial satellites destined for a geostationary orbit. As the vast majority of geostationary satellite launches are carried out from spaceports at a significant distance away from Earth's equator, the carrier rocket would only be able to launch the satellite into an elliptical orbit of maximum apogee 35,784-kilometres and with a non-zero inclination approximately equal to the latitude of the launch site.) (****TT&C: it"s a sub-system where the functions performed by the satellite control network to maintain health and status, measure specific mission parameters and processing over time a sequence of these measurement to refine parameter knowledge, and transmit mission commands to the satellite. Detailed study of TT&C in the upcoming units.)
It is better to launch rockets closer to the equator because the Earth rotates at a greater speed here than that at either pole. This extra speed at the equator means a rocket needs less thrust (and therefore less fuel) to launch into orbit. In addition, launching at the equator provides an additional 1,036 mph (1,667 km/h) of speed once the vehicle reaches orbit. This speed bonus means the vehicle needs less fuel, and that freed space can be used to carry more pay load.

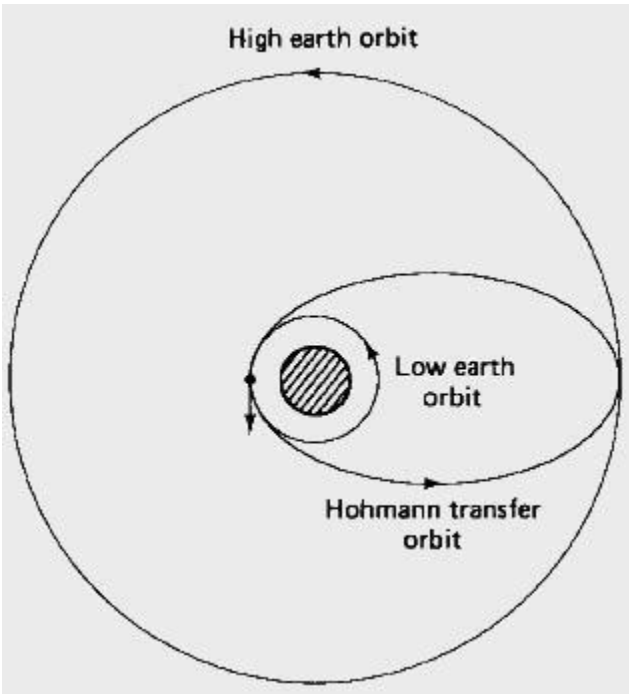


Figure : Hohmann Transfer Orbit

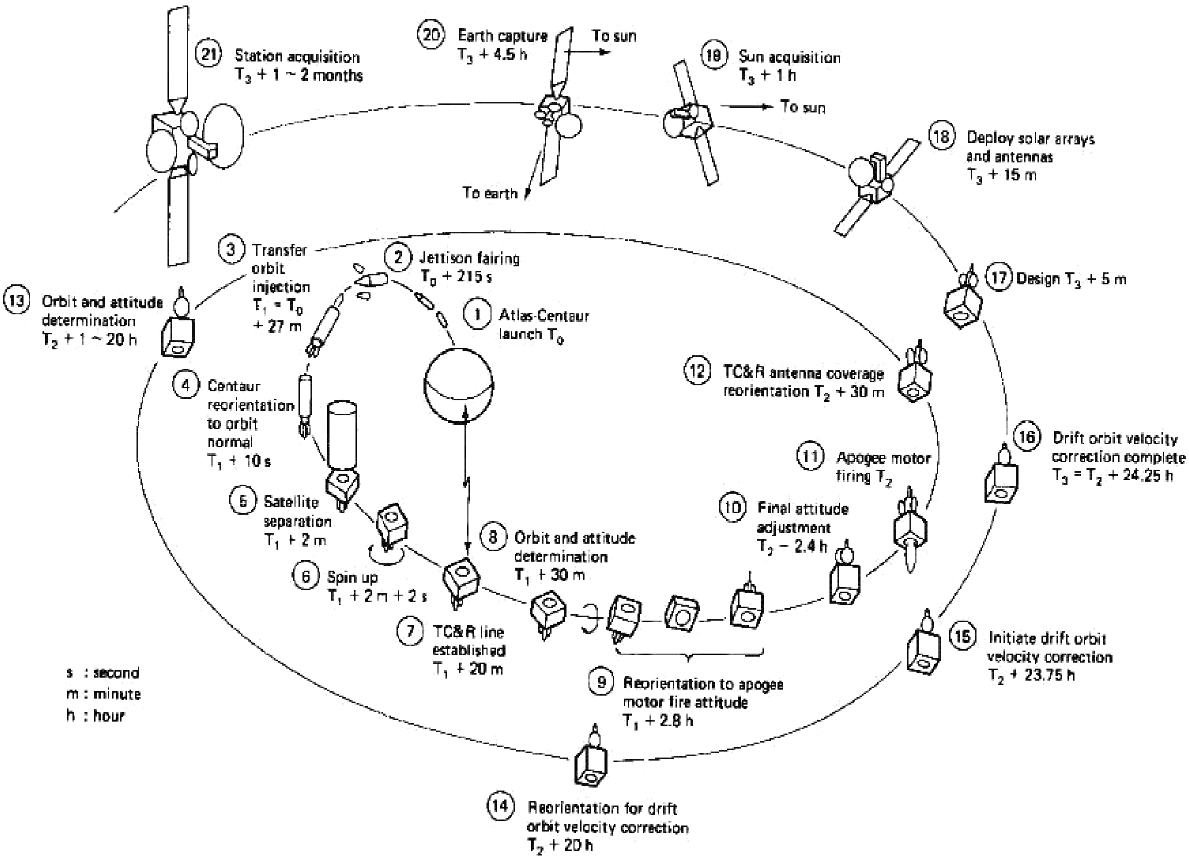


Figure : Launching stages of a GEO (example INTELSAT)

ORBITAL EFFECTS IN COMMUNICATION SYSTEMS PERFORMANCE

There are a number of perbuting forces that cause an orbit to depart from ideal Keplerian orbit. The most effecting ones are gravitational fields of sun and moon, non-spherical shape of the Earth, reaction of the satellite itself to motor movements within the satellites.

Thus the earth station keeps manoeuvring the satellite to maintain its position. Within a set of nominal geostationary coordinates. Thus the exact GEO is not attainable in practice and the orbital parameters vary with time. Hence these satellites are called “Geosynchronous” satellites or “Near-Geostationary satellites”.

Doppler Effect

To a stationary observer, the frequency of a moving radio transmitter varies with the transmitter’s velocity relative to the observer. If the true transmitter frequency (i.e., the frequency that the transmitter would send when at rest) is f_T, the received frequency f_R is higher than f_T when the transmitter is moving toward the receiver and lower than f_T when the transmitter is moving away from the receiver.

Range variations

Even with the best station keeping systems available for geostationary satellites, the position of a satellite with respect to earth exhibits a cyclic daily variation. The variation in position will lead to a variation in range between the satellite and user terminals. If time division multiple access(TDMA) is being used, careful attention must be paid to the timing of the frames within the TDMA bursts so that the individual user frames arrive at the satellite in the correct sequence and at the correct time.

Earth Eclipse of A Satellite

It occurs when Earth"s equatorial plane coincides with the plane f he Earth"s orbit around the sun. Near the time of spring and autumnal equinoxes, when the sun is crossing the equator, the satellite passes into sun"s shadow. This happens for some duration of time every day.

These eclipses begin 23 days before the equinox and end 23 days after the equinox. They last for almost 10 minutes at the beginning and end of equinox and increase for a maximum period of 72 minutes at a full eclipse. The solar cells of the satellite become non-functional during the eclipse period and the satellite is made to operate with the help of power supplied from the batteries.

A satellite will have the eclipse duration symmetric around the time t=Satellite Longitude/15

• 12 hours. A satellite at Greenwich longitude 0 will have the eclipse duration symmetric around 0/15 UTC +12hours = 00:00 UTC. The eclipse will happen at night but for satellites in the east it will happen late evening local time. For satellites in the west eclipse will happen in the early morning hour"s local time. An earth caused eclipse will normally not happen during peak viewing hours if the satellite is located near the longitude of the coverage area. Modern satellites are well equipped with batteries for operation during eclipse.

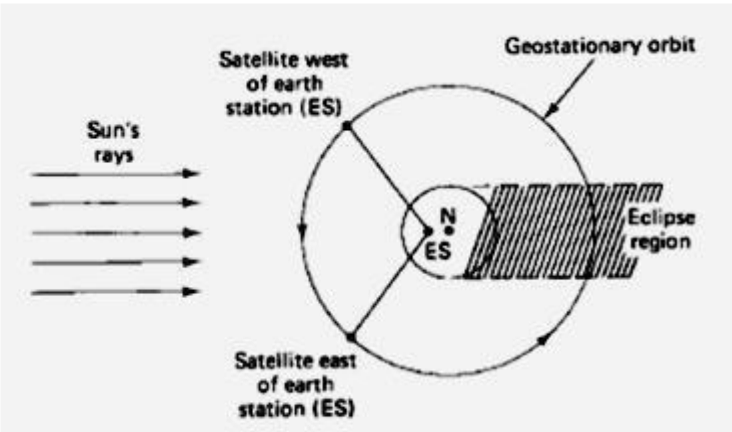


Figure : A satellite east of the earth station enters eclipse during daylight busy) hours at the earth station. A Satellite west of earth station enters eclipse during night and early morning hours (non busy time).

Sun Transit Outage

Sun transit outage is an interruption in or distortion of geostationary satellite signals caused by interference from solar radiation. Sun appears to be an extremely noisy source which completely blanks out the signal from satellite. This effect lasts for 6 days around the equinoxes. They occur for a maximum period of 10 minutes.

Generally, sun outages occur in February, March, September and October, that is, around the time of the equinoxes. At these times, the apparent path of the sun across the sky takes it directly behind the line of sight between an earth station and a satellite. As the sun radiates strongly at the microwave frequencies used to communicate with satellites (C-band, Ka band and Ku band) the sun swamps the signal from the satellite.

The effects of a sun outage can include partial degradation, that is, an increase in the error rate, or total destruction of the signal.

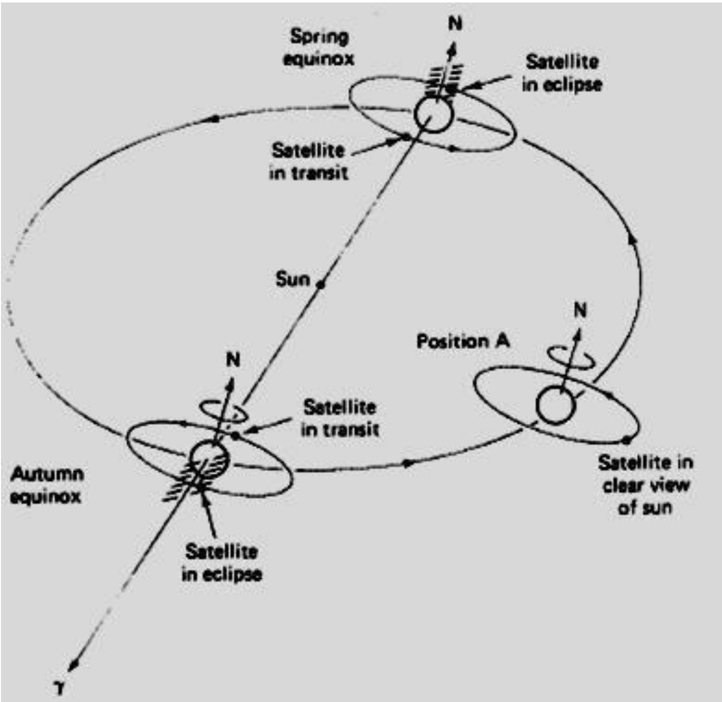


Figure: Earth Eclipse of a Satellite and Sun transit Outage

REFERENCES:

 www.wikipedia.com
 http://www.tech-faq.com/vsat.html
 M. Richharia, Mobile Satellite Communication: Principles and Trends, Pearson Education
 Rappaort, Wireless Communications Principals and Practices
 YI Bing Lin , Wireless and Mobile Network Architectures, John Wiley
 P. Nicopolitidis ,Wireless Networks, John Wiley
 Satellite Communications Dennis Roddy 3rd edition, Mc-Graw Hill publication
 Satellite communications-Timothy Pratt, Charles Bostian and Jeremy Allnutt, WSE, Wiley Publications, 2nd Edition,2003.
 Satellite communications - Design Principles-M.Richharia, BS Publications, 2nd Edition, 2003.

 Satellite communication- D.C Agarwal, Khanna Publications, 5th Ed.
 Satellite Communications Systems Engineering - Atmospheric Effects, Satellite Link Design and System Performance “Louis J. Ippolito”

WEBLINKS:

1. http://en.wikipedia.org/wiki/Communications_satellite#Applications

UNIT II
SATELLITE SUBSYSTEMS

An operating communications satellite system consists of several elements or segments, ranging from an orbital configuration of space components to ground based components and network elements. The particular application of the satellite system, for example fixed satellite service, mobile service, or broadcast service, will determine the specific elements of the system. A generic satellite system, applicable to most satellite applications, can be described by the elements shown in Figure 3.1.

The basic system consists of a satellite (or satellites) in space, relaying information between two or more users through ground terminals and the satellite. The information relayed may be voice, data, video, or a combination of the three. The user information may require transmission via terrestrial means to connect with the ground terminal. The satellite is controlled from the ground through a satellite control facility, often called the master control center (MCC), which provides tracking, telemetry, command, and monitoring functions for the system.

The ***space segment*** of the satellite system consists of the orbiting satellite (or satellites) and the ground satellite control facilities necessary to keep the satellites operational. The ***ground segment***, or earth segment, of the satellite system consists of the transmit and receive earth stations and the associated equipment to interface with the user network.

Ground segment elements are unique to the type of communications satellite application, such as fixed service, mobile service, broadcast service, or satellite broadband, and will be covered in later chapters where the specific applications are discussed. The space segment equipment carried aboard the satellite can be classified under two functional areas: the ***bus*** and the ***payload***, as shown in Figure 3.2.

• ***Bus*** The bus refers to the basic satellite structure itself and the subsystems that support the satellite. The bus subsystems are: the physical structure, power subsystem, attitude and orbital control subsystem, thermal control subsystem, and command and telemetry subsystem.

Payload The payload on a satellite is the equipment that provides the service or services intended for the satellite. A communications satellite payload consists of the communications equipment that provides the relay link between the up- and downlinks from the ground. The communications payload can be further divided into the transponder and the antenna subsystems.

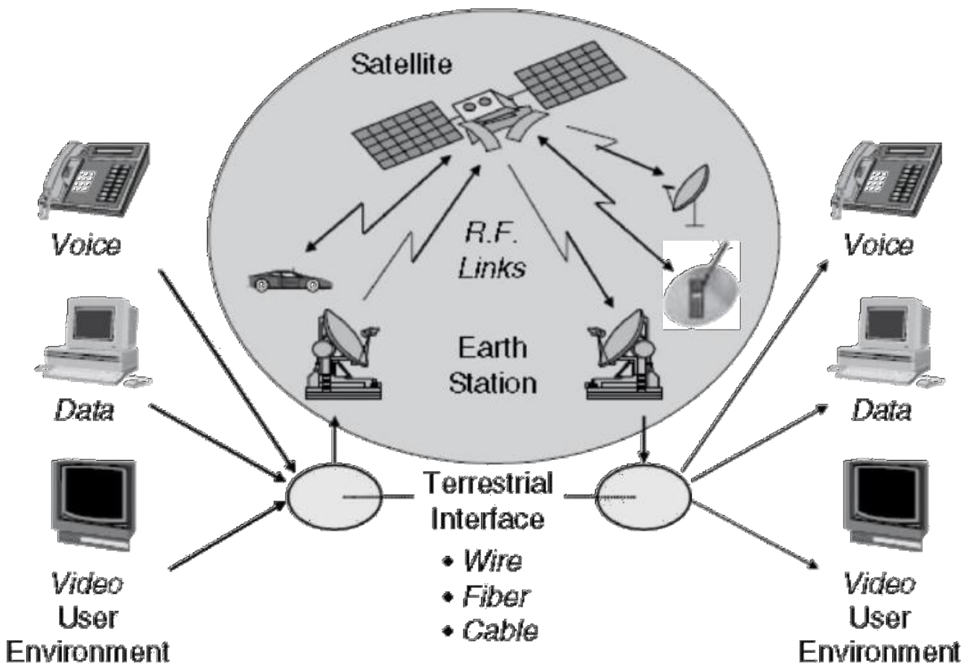


Figure 3.1 Communications via satellite

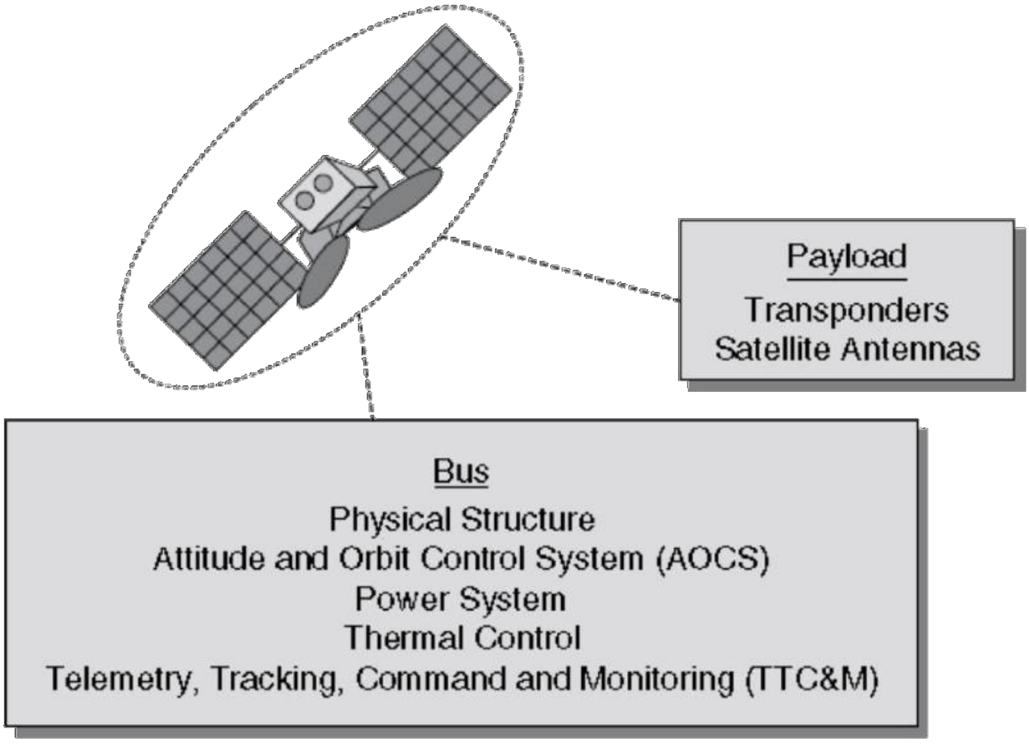


Figure 3.2 Communications satellite subsystems

A satellite may have more than one payload. The early Tracking and Data Relay Satellites (TDRS), for example, had an 'Advanced Westar' communications payload in addition to the tracking and data payload, which was the major mission of the satellite.

ATTITUDE AND ORBIT CONTROL SYSTEM

Satellite Bus

The basic characteristics of each of the bus subsystems are described in the following subsections.

Physical Structure

The physical structure of the satellite provides a 'home' for all the components of the satellite.

The basic shape of the structure depends of the method of stabilization employed to keep the satellite stable and pointing in the desired direction, usually to keep the antennas properly oriented toward earth. Two methods are commonly employed: ***spin stabilization*** and ***three axis*** or ***body stabilization***. Both methods are used for GSO and NGSO satellites.

Figure 3.3 highlights the basic configurations of each, along with an example of a satellite of each type.

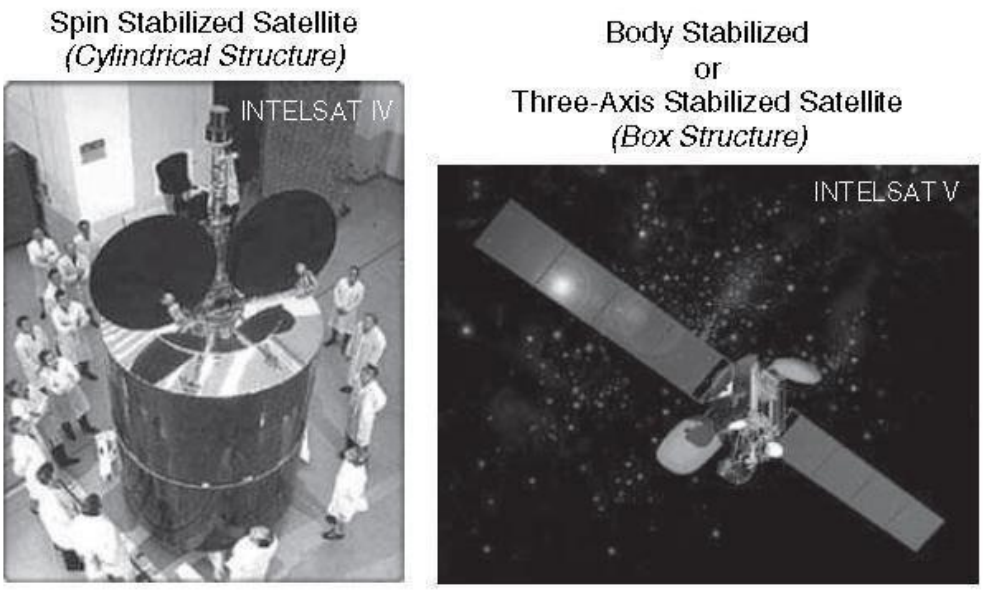


Figure 3.3 Physical structure

Spin Stabilization

A spin stabilized satellite is usually cylindrical in shape, because the satellite is required to be mechanically balanced about an axis, so that it can be maintained in orbit by spinning on its axis. For GSO satellites, the spin axis is maintained parallel to the spin axis of the earth, with spin rates in the range of 30 to 100 revolutions per minute.

The spinning satellite will maintain its correct attitude without additional effort, unless disturbance torques are introduced. External forces such as solar radiation, gravitational gradients, and meteorite impacts can generate undesired torques. Internal effects such as motor bearing friction and antenna subsystem movement can also produce unwanted torque in the system. Impulse type thrusters, or jets, are used to maintain spin rate and correct any wobbling or nutation to the satellite spin axis.

The entire spacecraft rotates for spin-stabilized satellites that employ omnidirectional antennas.
When directional antennas are used, which is the prevalent case, the antenna subsystem must be ***despun***, so that the antenna is kept properly pointed towards earth. Figure 3.4 shows a typical implementation of a despun platform on a spin-stabilized satellite. The antenna subsystem is mounted on a platform or shelf, which may also contain some of the transponder equipment. The satellite is spun-up by small radial gas jets on the surface of the drum. The rotation, ranging from 30 to 100 rpm, provides gyroscopic force stability for the satellite.
The propellants used include heated hydrazine or a bipropellant mix of hydrazine and nitrogen tetroxide. The despun platform is driven by an electric motor in the opposite direction of the satellite spin, on the same spin axis and at the same spin rate as the satellite body, to maintain a fixed orientation for the antennas, relative to earth.

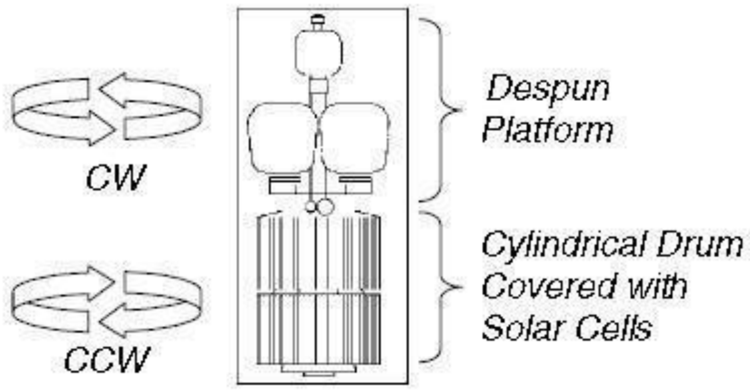


Figure 3.4 Despun platform on spin-stabilized satellite

Three-axis Stabilization
A three-axis stabilized satellite is maintained in space with stabilizing elements for each of the three axes, referred to as roll, pitch, and yaw, in conformance with the definitions first used in the aircraft industry. The entire body of the spacecraft remains fixed in space, relative to the earth, which is why the three-axis stabilized satellite is also referred to as a body-stabilized satellite.
Active attitude control is required with three-axis stabilization. Control jets or reaction wheels are used, either separately or in combination, to provide correction and control for ach of the three axes. A reaction wheel is basically a flywheel that absorbs the undesired torques that would shift spacecraft orientation. Fuel is expended for both the control jets and for the reaction wheels, which must periodically be ‘unloaded’ of momentum energy that builds up in the wheel.
The three-axis stabilized satellite does not need to be symmetric or cylindrical, and most tend be box-like, with numerous appendages attached. Typical appendages include antenna systems and solar cell panels, which are often unfurled after placement at the on-orbit location.
Attitude Control
The ***attitude*** of a satellite refers to its orientation in space with respect to earth. Attitude control is necessary so that the antennas, which usually have narrow directional beams, are

pointed correctly towards earth. Several forces can interact to affect the attitude of the spacecraft, including gravitational forces from the sun, moon, and planets; solar pressures acting on the spacecraft body, antennas or solar panels; and earth's magnetic field.

Orientation is monitored on the spacecraft by infrared ***horizon detectors***, which detect the rim of earth against the background of space. Four detectors are used to establish a reference point, usually the center of the earth, and any shift in orientation is detected by one or more of the sensors.Acontrol signal is generated that activates attitude control devices to restore proper orientation. Gas jets, ion thrusters, or momentum wheels are used to provide active attitude control on communications satellites.

Since the earth is not a perfect sphere, the satellite will be accelerated towards one of two 'stable' points in the equatorial plane. The locations are 105◦W and 75◦ E. Figure 3.5 shows the geometry of the stable points and the resulting drift patterns. If no orbit control (station keeping) is provided, the satellite will drift to and eventually settle at one of the stable points. This could take several years and several passes through the stable point before the satellite finally comes to rest at a stable point. The stable points are sometimes referred to as the 'satellite graveyard', for obvious reasons.

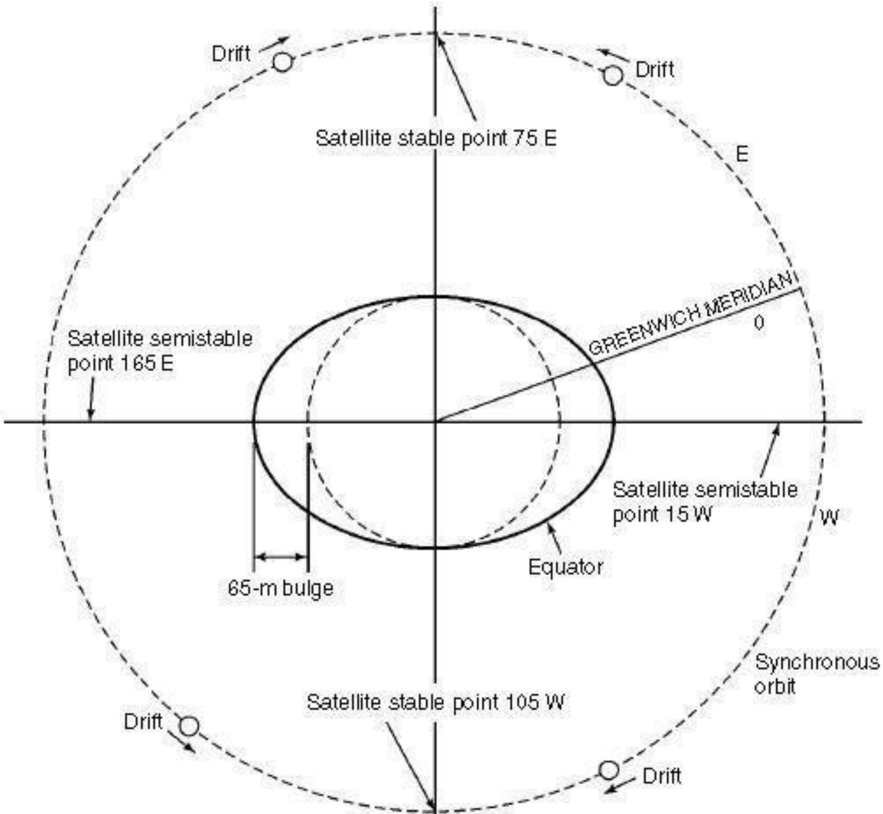


Figure 3.5 GSO satellite stable points *(source: Pratt* et al. *[2]; reproduced by permission of © 2003 John Wiley & Sons, Inc.)*

Orbital Control

Orbital control, often called ***station keeping***, is the process required to maintain a satellite in its proper orbit location. It is similar to, although not functionally the same as, attitude control, discussed in the previous section. GSO satellites will undergo forces that would cause the satellite to drift in the east-west (longitude) and north-south (latitude) directions, as well as in altitude, if not compensated for with active orbital control jets. Orbital control is usually maintained with the same thruster system as is attitude control.

The non-spherical (oblate) properties of the earth, primarily exhibited as an equatorial bulge, cause the satellite to drift slowly in longitude along the equatorial plane. Control jets are pulsed to impart an opposite velocity component to the satellite, which causes the satellite to drift back to its nominal position. These corrections are referred to as ***east-west station keeping*** maneuvers, which are accomplished periodically every two to three weeks. Typical C-band satellites must be maintained within •}0.1◦, and Ku-band satellites within •}0.05◦, of nominal longitude, to keep the satellites within the beamwidths of the ground terminal antennas. For a nominal geostationary radius of 42 000 km, the total longitude variation would be about 150 km for C-band and about 75 km for Ku-band. Latitude drift will be induced primarily by gravitational forces from the sun and the moon.

These forces cause the satellite inclination to change about 0.075◦ per month if left uncorrected. Periodic pulsing to compensate for these forces, called ***north-south station keeping*** maneuvers, must also be accomplished periodically to maintain the nominal satellite orbit location. North south station-keeping tolerance requirements are similar to those for east-west station keeping, 0.1◦ for C-band, and •}0.05◦ for Ku-band.

Satellite altitude will vary about •}0.1 %, which is about 72 km for a nominal 36 000-km geostationary altitude.AC-band satellite, therefore, must be maintained in a ‘box’ with longitudinal and latitudinal sides of about 150 km and an altitude side of 72 km. TheKu-band satellite requires a box with approximately equal sides of 75 km. Figure 3.6 summarizes the orbital control limits and indicates the typical ‘orbital box’ that a GSO satellite can be maintained in for the C-band and Ku-band cases.

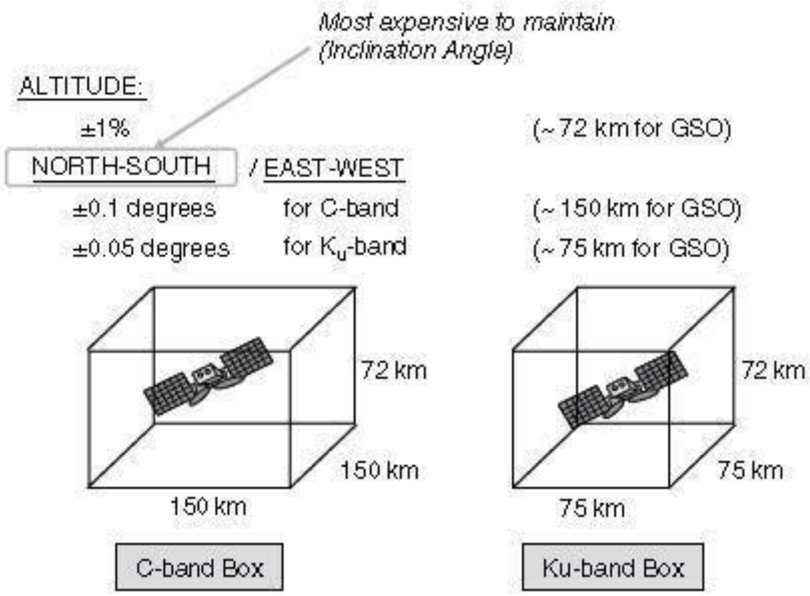


Figure 3.6 Orbital control parameters for GSO satellites

North-south station keeping requires much more fuel than east-west station keeping, and often satellites are maintained with little or no north-south station keeping to extend on-orbit life.

The satellite is allowed to drift with a higher inclination, with the drift compensated for on the ground with tracking and/or smaller aperture antennas. The expendable fuel that must be carried on-board the satellite to provide orbital and attitude control is usually the determining factor in the on-orbit lifetime of a communications satellite.

As much as one-half of the satellite launch weight is station-keeping fuel. The lifetimes of most of the critical electronic and mechanical components usually exceed the allowable time for active orbit control, which is limited by the weight of fuel that can be carried to orbit with current conventional launch vehicles. It is not unusual for a communications satellite to 'run out of fuel' with most of its electronic communications subsystems still functioning.

Thermal Control

Orbiting satellites will experience large temperature variations, which must be controlled in the harsh environment of outer space. Thermal radiation from the sun heats one side of the spacecraft, while the side facing outer space is exposed to the extremely low temperatures of space. Much of the equipment in the satellite itself generates heat, which must be controlled.

Low orbiting satellites can also be affected by thermal radiation reflected from the earth itself.

The satellite thermal control system is designed to control the large thermal gradients generated in the satellite by removing or relocating the heat to provide an as stable as possible temperature environment for the satellite. Several techniques are employed to provide thermal control in a satellite. ***Thermal blankets*** and ***thermal shields*** are placed at critical locations to provide insulation. ***Radiation mirrors*** are placed around electronic subsystems, particularly for spin-stabilized satellites, to protect critical equipment. ***Heat pumps*** are used to relocate heat from power devices such as traveling wave power amplifiers to outer walls or heat sinks to provide a more effective thermal path for heat to escape. Thermal ***heaters*** may also be used to maintain adequate temperature conditions for some components, such as propulsion lines or thrusters, where low temperatures would cause severe problems.

The satellite antenna structure is one of the critical components that can be affected by thermal radiation from the sun. Large aperture antennas can be twisted or contorted as the sun moves around the satellite, heating and cooling various portions of the structure. This 'potato chip' effect is most critical for apertures exceeding about 15m designed to operate at high frequencies, i.e., Ku-band, Ka-band, and above, because the small wavelengths react more severely resulting in antenna beam point distortions and possible gain degradation.

TELEMETRY, TRACKING, COMMAND AND MONITORING

The tracking, telemetry, command, and monitoring (TTC&M) subsystem provides essential spacecraft management and control functions to keep the satellite operating safely in orbit. The TTC&M links between the spacecraft and the ground are usually separate from the communications system links. TTC&M links may operate in the same frequency bands or in other bands.

TTC&M is most often accomplished through a separate earth terminal facility specifically designed for the complex operations required to maintain a spacecraft in orbit. One TTC&M facility may maintain several spacecraft simultaneously in orbit through TTC&M links to each vehicle. Figure 3.7 shows the typical TTC&M functional elements for the satellite and ground facility for a communications satellite application.

The satellite TTC&M subsystems comprise the antenna, command receiver, tracking and telemetry transmitter, and possibly tracking sensors. Telemetry data are received from the other subsystems of the spacecraft, such as the payload, power, attitude control, and thermal control. Command data are relayed from the command receiver to other subsystems to control such parameters as antenna pointing, transponder modes of operation, battery and solar cell changes, etc.

The elements on the ground include the TTC&M antenna, telemetry receiver, command transmitter, tracking subsystem, and associated processing and analysis functions. Satellite control and monitoring is accomplished through monitors and keyboard interface. Major operations of TTC&M may be automated, with minimal human interface required.

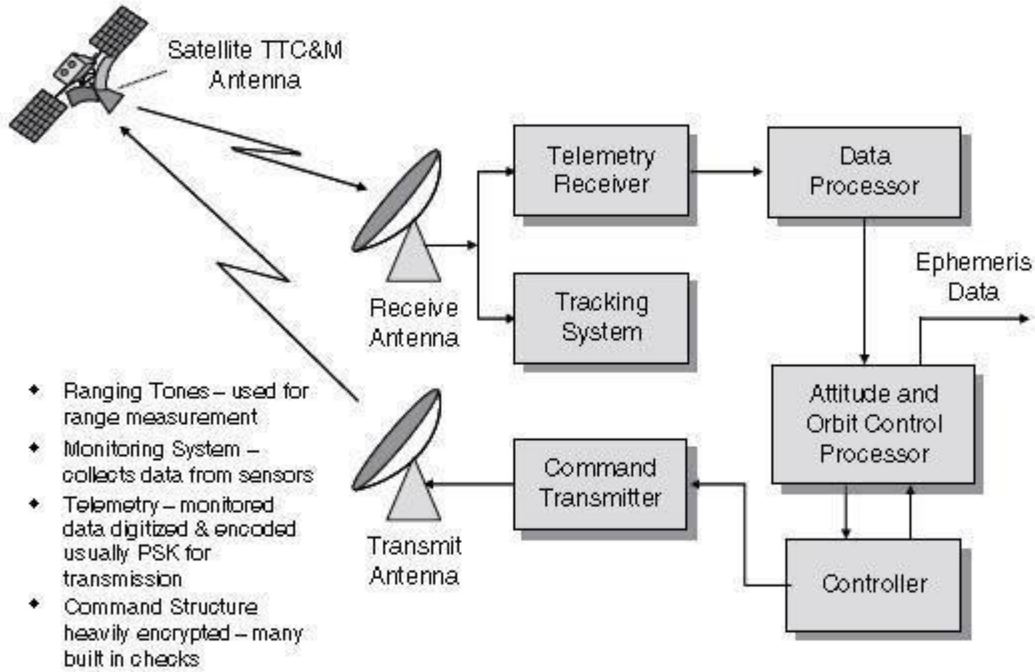


Figure 3.7 Tracking, telemetry, command, and monitoring (TTC&M)

Tracking refers to the determination of the current orbit, position, and movement of the spacecraft. The tracking function is accomplished by a number of techniques, usually involving satellite beacon signals, which are received at the satellite TTC&M earth station. The Doppler shift of the beacon (or the telemetry carrier) is monitored to determine the rate at which the range is changing (the range rate). Angular measurements from one or more earth terminals can be used to determine spacecraft location. The range can be determined by observing the time delay of a pulse or sequence of pulses transmitted from the satellite. Acceleration and velocity sensors on the satellite can be used to monitor orbital location and changes in orbital location.

The ***telemetry*** function involves the collection of data from sensors on-board the spacecraft and the relay of this information to the ground. The telemetered data include such parameters as voltage and current conditions in the power subsystem, temperature of critical subsystems, status of switches and relays in the communications and antenna subsystems, fuel tank pressures, and attitude control sensor status. A typical communications satellite telemetry link could involve over 100 channels of sensor information, usually in digital form, but occasionally in analog form for diagnostic evaluations. The telemetry carrier modulation is typically frequency or phase shift keying (FSK or PSK), with the telemetry channels transmitted in a time division multiplex (TDM) format. Telemetry channel data rates are low, usually only a few kbps.

Command is the complementary function to telemetry. The command system relays specific control and operations information from the ground to the spacecraft, often in response to telemetry information received from the spacecraft. Parameters involved in typical command links include changes and corrections in attitude control and orbital control;

- antenna pointing and control;
- transponder mode of operation;
- battery voltage control.

The command system is used during launch to control the firing of the boost motor, deploy appendages such as solar panels and antenna reflectors, and 'spin-up' a spin-stabilized spacecraft body. Security is an important factor in the command system for a communications satellite. The structure of the command system must contain safeguards against intentional or unintentional signals corrupting the command link, or unauthorized commands from being transmitted and accepted by the spacecraft. Command links are nearly always encrypted with a secure code format to maintain the health and safety of the satellite. The command procedure also involves multiple transmissions to the spacecraft, to assure the validity and correct reception of the command, before the execute instruction is transmitted. Telemetry and command during the launch and transfer orbit phases usually requires a backup TTC&M system, since the main TTC&M system may be inoperable because the antenna is not deployed, or the spacecraft attitude is not proper for transmission to earth. The backup system usually operates with an omnidirectional antenna, at UHF or S-band, with sufficient margin to allow operation in the most adverse conditions. The backup system could also be used if the main TTC&M system fails on orbit.

POWER SYSTEMS

The electrical power for operating equipment on a communications satellite is obtained primarily from solar cells, which convert incident sunlight into electrical energy. The radiation on a satellite from the sun has an intensity averaging about 1.4 kW/m2. Solar cells operate at an efficiency of 20–25% at ***beginning of life*** (BOL), and can degrade to 5–10% at ***end of life*** (EOL), usually considered to be 15 years. Because of this, large numbers of cells, connected in serial-parallel arrays, are required to support the communications satellite electronic systems, which often require more than one to two kilowatts of prime power to function. The spin-stabilized satellite usually has cylindrical panels, which may be extended after deployment to provide additional exposure area. A cylindrical spin-stabilized satellite must carry a larger number of solar cells than an equivalent three-axis stabilized satellite, because only about one-third of the cells are exposed to the sun at any one time.

The three-axis stabilized satellite configuration allows for better utilization of solar cell area, because the cells can be arranged in flat panels, or sails, which can be rotated to maintain normal exposure to the sun – levels up to 10kW are attainable with rotating panels. All spacecraft must also carry storage batteries to provide power during launch and during eclipse periods when sun blockage occurs. Eclipses occur for a GSO satellite twice a year, around the spring and fall equinoxes, when earth's shadow passes across the spacecraft. Daily eclipses start about 23 days before the equinox, and end the same number of days after. The daily eclipse duration increases a few minutes each day to about a 70-minute peak on equinox day, then decreases a similar amount each day following the peak. Sealed nickel cadmium (Ni-Cd) batteries are most often used for satellite battery systems. They have good reliability and long life, and do not outgas when in a charging cycle. Nickel-hydrogen (NiH2) batteries, which provide a significant improvement in power-to-weight ratio, are also used. A power conditioning unit is also included in the power subsystem, for the control of battery charging and for power regulation and monitoring.

The power generating and control systems on a communications satellite account for a large part of its weight, often 10 to 20% of total dry weight.

COMMUNICATION SUBSYSTEM

Satellite Payload

The next two sections discuss the key elements of the payload portion of the space segment, specifically for communications satellite systems: the transponder and antenna subsystems.

Transponder

The ***transponder*** in a communications satellite is the series of components that provides the communications channel, or link, between the uplink signal received at the uplink antenna, and the downlink signal transmitted by the downlink antenna. A typical communications satellite will contain several transponders, and some of the equipment may be common to more than one transponder.

Each transponder generally operates in a different frequency band, with the allocated frequency spectrum band divided into slots, with a specified center frequency and operating bandwidth. The C-band FSS service allocation, for example, is 500MHz wide. A typical design would accommodate 12 transponders, each with a bandwidth of 36 MHz, with guard bands of 4MHz between each.Atypical commercial communications satellite today can have 24 to 48 transponders, operating in the C-band, Ku-band, or Ka-bands. The number of transponders can be doubled by the use of ***polarization frequency reuse***, where two carriers at the same frequency, but with orthogonal polarization, are used. Both linear polarization (horizontal and vertical sense) and circular polarization (right-hand and left-hand sense) have been used. Additional frequency reuse may be achieved through spatial separation of the signals, in the form of narrow spot beams, which allow the reuse of the same frequency carrier for physically separate locations on the earth. Polarization reuse and spot beams can be combined to provide four times, six times, eight times, or even higher frequency reuse factors in advanced satellite systems.

The communications satellite transponder is implemented in one of two general types of configurations: the frequency translation transponder and the on-board processing transponder.

Frequency Translation Transponder

The first type, which has been the dominant configuration since the inception of satellite communications, is the ***frequency translation*** transponder. The frequency translation transponder, also referred to as a ***non-regenerative repeater***, or ***bent pipe***, receives the uplink signal and, after amplification, retransmits it with only a translation in carrier frequency. Figure 3.8 shows the typical implementation of a dual conversion frequency translation transponder, where the uplink radio frequency, fup, is converted to an intermediate lower frequency, fif , amplified, and then converted back up to the downlink RF frequency, fdwn, for transmission to earth.

Frequency translation transponders are used for FSS, BSS, and MSS applications, in both GSO and NGSO orbits. The uplinks and downlinks are codependent, meaning that any degradation introduced on the uplink will be transferred to the downlink, affecting the total communications link.

This has significant impact on the performance of the end-to-end link

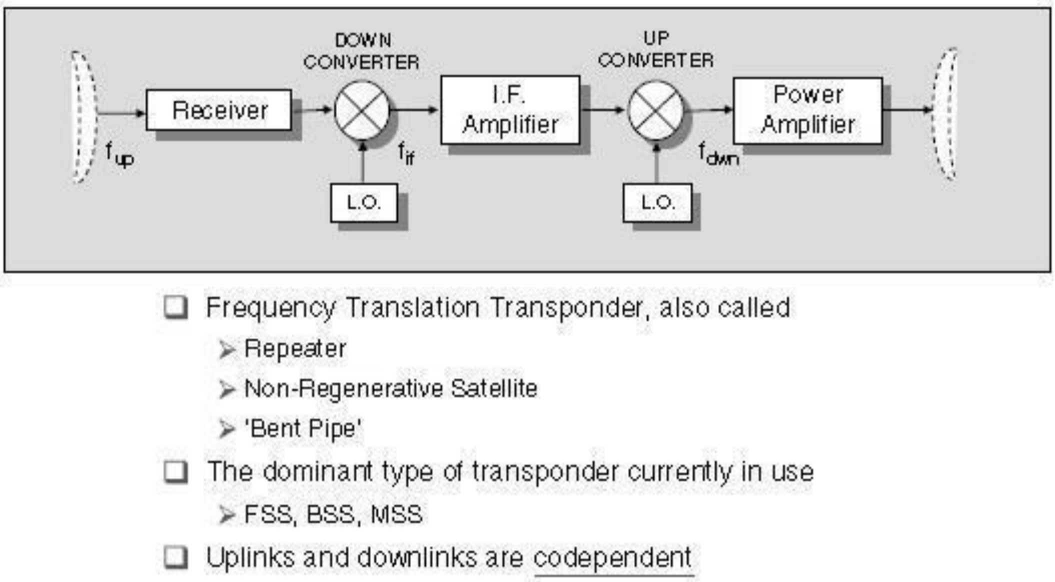


Figure 3.8 Frequency translation transponder

On-board Processing Transponder

Figure 3.9 shows the second type of satellite transponder, the ***on-board processing*** transponder, also called a ***regenerative repeater demod/remod transponder***, or ***smart satellite***. The uplink signal at fup is demodulated to baseband, fbaseband . The baseband signal is available for processing on-board, including reformatting and error-correction. The baseband information is then remodulated to the downlink carrier at fdwn, possibly in a different modulation format to the uplink and, after final amplification, transmitted to the ground. The demodulation/remodulation process removes uplink noise and interference from the downlink, while allowing additional on-board processing to be accomplished. Thus the uplinks and downlinks are independent with respect to evaluation of overall link performance, unlike the frequency translation transponder where uplink degradations are codependent, as discussed earlier.

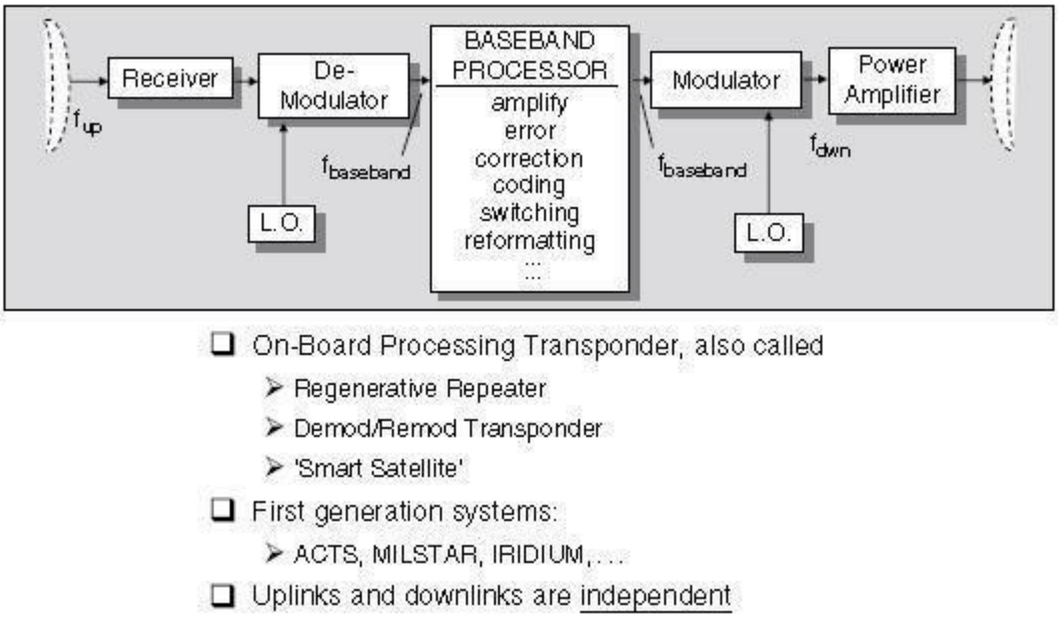
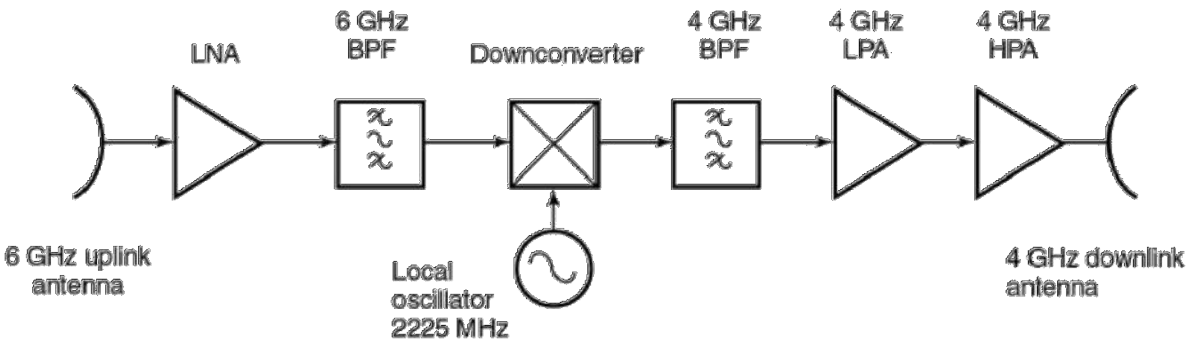


Figure 3.9 On-board processing transponder

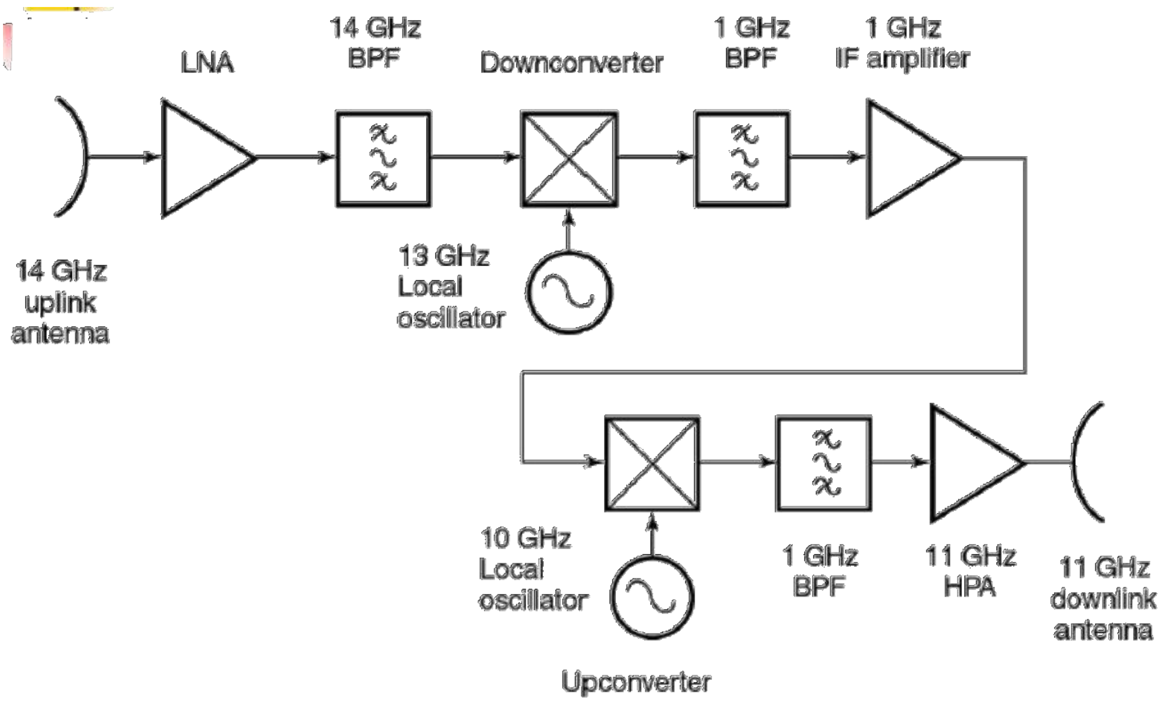
On-board processing satellites tend to be more complex and expensive than frequency translation satellites; however, they offer significant performance advantages, particularly for small terminal users or for large diverse networks. The performance of the on-board processing satellite's composite link is discussed further in Chapter 9.

Traveling wave tube amplifiers (TWTAs) or ***solid state amplifiers*** (SSPAs) are used to provide the final output power required for each transponder channel. The TWTA is a slow wave structure device, which operates in a vacuum envelope, and requires permanent magnet focusing and high voltage DC power supply support systems. The major advantage of the TWTA is its wide bandwidth capability at microwave frequencies. TWTAs for space applications can operate to well above 30 GHz, with output powers of 150 watts or more, and RF bandwidths exceeding 1 GHz. SSPAs are used when power requirements in the 2–20 watt region are required. SSPAs operate with slightly better power efficiency than the TWTA, however both are nonlinear devices, which directly impacts system performance, as we shall see when RF link performance is discussed in later chapters.

Other devices may be included in the basic transponder configurations of Figures 3.8 and 3.9, including band pass filters, switches, input multiplexers, switch matrices, and output multiplexers. Each device must be considered when evaluating the signal losses and system performance of the space segment of the satellite network.



Simplified single conversion transponder (bent pipe) for 6/4 GHz band.



Simplified double conversion transponder (bent pipe) for 14/11 GHz band.

SATELLITE ANTENNA

Antennas

The antenna systems on the spacecraft are used for transmitting and receiving the RF signals that comprise the space links of the communications channels. The antenna system is a critical part of the satellite communications system, because it is the essential element in increasing the strength of the transmitted or received signal to allow amplification, processing, and eventual retransmission.

The most important parameters that define the performance of an antenna are antenna ***gain***, antenna ***beamwidth***, and antenna ***sidelobes***. The gain defines the increase in strength achieved in concentrating the radio wave energy, either in transmission or reception, by the antenna system.

The antenna gain is usually expressed in ***dBi***, decibels above an isotropic antenna, which is an antenna that radiates uniformly in all directions. The beamwidth is usually expressed as the ***half-power beamwidth*** or the ***3-dB beamwidth***, which is a measure of the angle over which maximum gain occurs. The sidelobes define the amount of gain in the off-axis directions.

Most satellite communications applications require an antenna to be highly directional (high gain, narrow beamwidth) with negligibly small sidelobes.

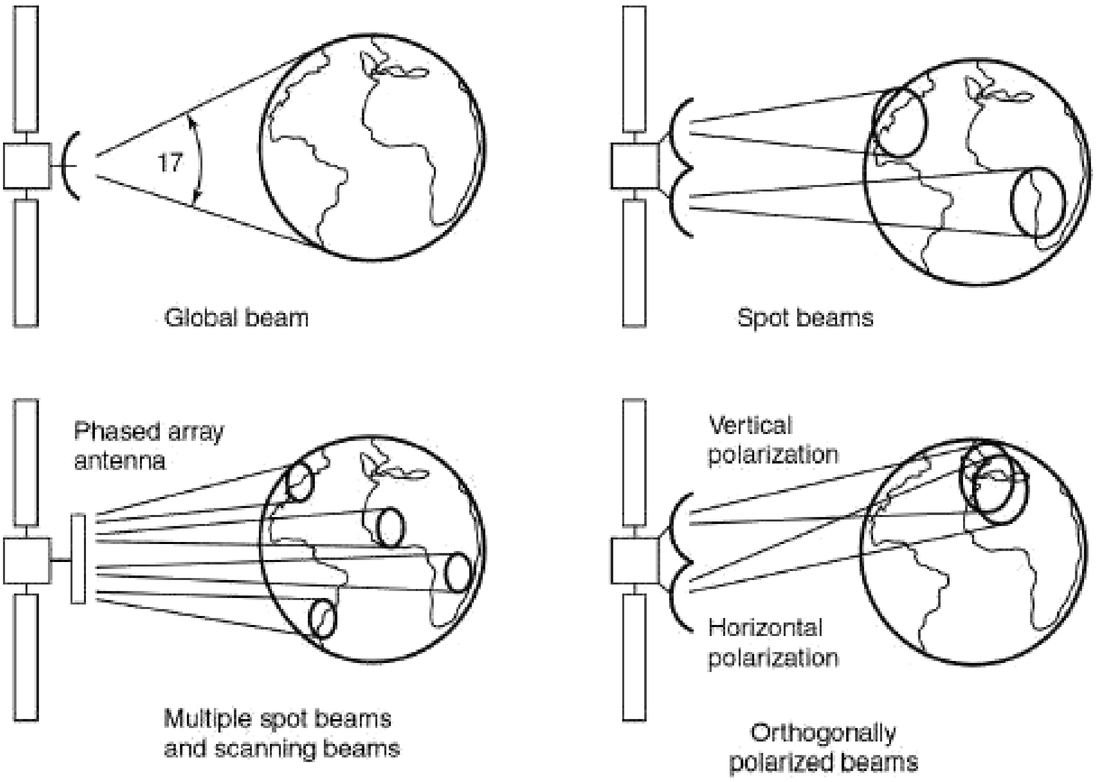
The common types of antennas used in satellite systems are the linear dipole, the horn antenna, the parabolic reflector, and the array antenna. The ***linear dipole antenna*** is an isotropic radiator that radiates uniformly in all directions. Four or more dipole antennas are placed on the spacecraft to obtain a nearly omni-directional pattern. Dipole antennas are used primarily at VHF and UHF for tracking, telemetry, and command links. Dipole antennas are also important during launch operations, where the spacecraft attitude has not yet been established, and for satellites that operate without attitude control or body stabilization (particularly for LEO systems).

Horn antennas are used at frequencies from about 4 GHz and up, when relatively wide beams are required, such as global coverage from a GSO satellite. A horn is a flared section of waveguide that provides gains of up to about 20 dBi, with beamwidths of 10◦ or higher. If higher gains or narrower bandwidths are required, a reflector or array antenna must be used.

The most often used antenna for satellite systems, particularly for those operating above 10 GHz, is the ***parabolic reflector antenna***. Parabolic reflector antennas are usually illuminated by one or more horn antenna feeds at the focus of the paroboloid. Parabolic reflectors offer a much higher gain than that achievable by the horn antenna alone. Gains of 25 dB and higher, with beamwidths of 1◦ or less, are achievable with parabolic reflector antennas operating in the C, Ku, or Ka bands. Narrow beam antennas usually require physical pointing mechanisms (gimbals) on the spacecraft to point the beam in the desired direction.

There is increasing interest in the use of ***array antennas*** for satellite communications applications.

A steerable, focused beam can be formed by combining the radiation from several small elements made up of dipoles, helices, or horns. Beam forming can be achieved by electronically phase shifting the signal at each element. Proper selection of the phase characteristics between the elements allows the direction and beamwidth to be controlled, without physical movement of the antenna system. The array antenna gain increases with the square of the number of elements. Gains and beamwidths comparable to those available from parabolic reflector antennas can be achieved with array antennas.



EQUIPMENT RELIABILITY AND SPACE QUALIFICATION

Communication satellites built already have provided operational lifetimes of up to 15years. Once a satellite is in geo stationary orbit, there is little possibility of repairing components that fail or adding more fuel for station keeping. The components that make up the satellite must therefore have very high reliability in the hostile environment of outer space, and a strategy must be devised that allows some components to fail without causing the entire communication capacity of the satellite to be lost. Two separate approaches are used: space qualification of every part of the satellite to ensure that it has a long life expectancy in orbit and redundancy of the most critical components to provide continued operation when one component fails.

Space Qualification:

Outer space, at geostationary orbit distances is a harsh environment. There is a total vacuum and the sun irradiates the satellite with 1.4kw of heat and light on each square meter of exposed surface. Electronic equipment cannot operate at such extremes of temperature and must be housed within the satellite and heated or cooled so that its temperature stays within the range 0^0 to 75^0C. This requires a thermal control system that manages heat flow throughout a GEO satellite as the sun moves around once every 24hr.

When a satellite is designed, three prototype models are often built and tested. The mechanical model contains all the structural and mechanical parts that will be included in the satellite and is tested to ensure that all moving parts operate correctly in a vacuum, over a wide temperature range. The thermal model contains all the electronics packages and other components that must be maintained at correct temperature. The electrical model contains all electronic parts of the satellite and is tested for correct electrical performance under total vacuum and a wide range of temperatures.

Many of the electronic and mechanical components that are used in satellite are known to have limited life times, or a finite probability of failure. If failure of one of these components will jeopardize the mission or reduce the communication capacity of the satellite, a backup, or redundant, unit will provided. The design of the system must be such that when one unit fails, the backup can automatically take over or be switched into operation by a command from the ground.

Reliability

Reliability is counted by considering the proper working of satellites critical components. Reliability could be improved by making the critical components redundant. Components with a limited lifetime such as travelling wave tube amplifier etc should be made redundant.

Travelling Wave Tube Amplifier (TWTA): travelling wave tube amplifiers have applications in both receiver and transmitter systems, and come in all shapes and sizes, but they all consist of three basic parts-the tube, the tube mount (which includes the beam focussing magnets) and the power supply.

The main attraction of these devices is their very high gain (30-60 dB), linear characteristics and 1-2 octave bandwidth. They are quite widely used professionally, but are still rather scarce in amateur circles. This article describes a little of the theory of twts, and explains how to use them, in the hope that more amateurs may be able to acquire and use these fascinating components.

When used as receiver RF amplifiers they are characterized by high gain, low noise figure and wide bandwidth, and are known as low noise amplifiers (LNAS). These usually come with tube, mount and power supply in one integral unit, with no external adjustments to make-just input socket, output socket and mains supply connections. A typical LNA has an octave bandwidth (eg 2-4 GHz), 30 dB gain, 8 dB noise figure, and a saturated power output of 10 mW, within a volume of 2 in by 2 in by 10 in.

Transmitter TWTAs are naturally somewhat bulkier, and often have the poweror supplies as a separate unit. Medium-power tubes have outputs of up to about 10 W, while high-power tubes deliver several hundred watts. Such tubes have gains of the order of 30 or 40 dB, and bandwidths of up to an octave.

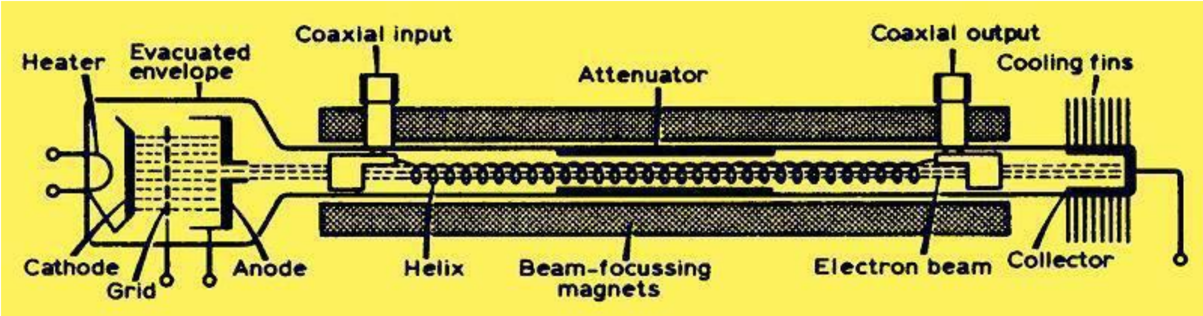


Figure TWTA

Other critical components are antenna reflectors, beaming assemblers etc.

A reliability model is used to calculate the satellite‟s reliability. It is defined as "the probability that a given component or system performs its functions as desired within a specific time t.

The failure rate for all components is calculated and they are categorized into the following three categories:

o Early high failure rate region: used for manufacturing faults, defects in material etc.
o Low failure: used for random component failure.
o High failure rate: used for components weave-out.

Certainly early failures criteria is eliminated as most of the components are tested before used in the satellite.

Random failures are more seen. They could be reduced by using reliable engineering techniques.

The life-spam of component could be increased by improving manufacturing techniques and the type of material used to reduce the number of worn out parts and hence reducing the high failure rate criteria.

It is sent that the failure rate is constant over time and is looking at this reliability can be determined.

The system is made of several components, connected in a series, then the overall reliability is determined.

By duplicating the less reliable and critical components, the overall reliability of the system could be improved. If any failure occurs in operational unit, then the standby unit takes over to develop a system with redundant components, its redundant elements are considered in parallel.

Parallel redundancy is useful when the reliability of an individual sub-system is high.

Example: consider a system having *i* parallel components in which reliability of each element is independent of others.

If Qi is the unreliability of the **ith** parallel element, then the probability that all units will fail is the product of the individual un-reliabilities:
Qs = Q1 Q2 Q3 …. Qi
When the un-reliability of all elements is equal, then Qs = Qi where Q is the un-reliability of each element.

By doing a complete failure analysis, one could find out which failure occurs more than the rest and such analysis help in finding out the manufacturing defects in the product of a given batch of components or probably a design defect.

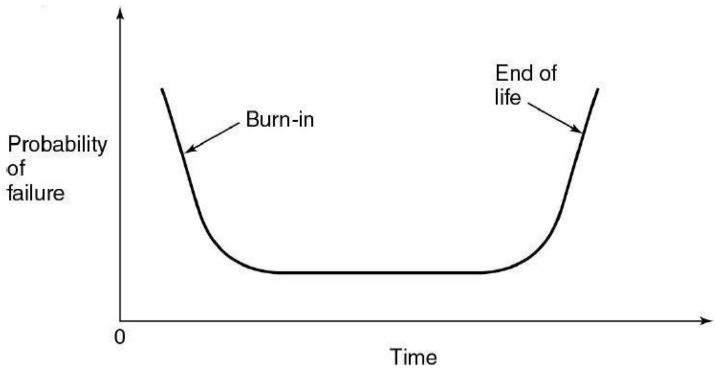
This analysis is done to reduce the overall reliability to a value less than that predicted by the above analysis.

Co-related failures could also be reduced by using units from different manufacturers. The design defects are generic to all satellite produced in a series. Generally these defects are detected and corrected to minimize their impact. This is done when a complete design change cannot be implemented.

Even through the reliability can be improved by adding redundant devices and components, the weight of the satellite increases which again becomes a problem. Redundant component also increase the cost of the satellite.

The two major cost components are:
o Cost of equipment together with the switching and failure sensing mechanism used.
o The associated increase in weight of the satellite resulting in an increased launch cost.

Optimization techniques are performed for cost minimization purpose.



Bathtub curve for probability of failure

Redundancy:

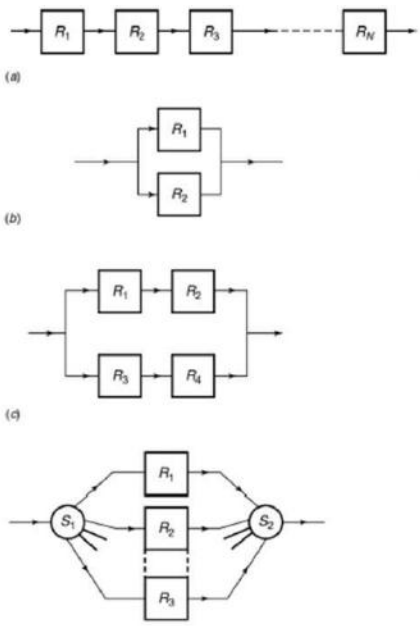
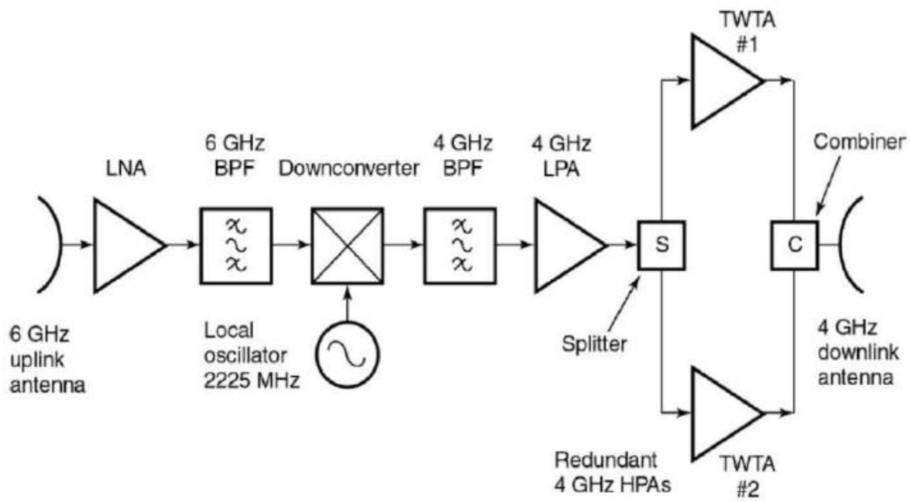


Figure
Redundancy connections. (*a*) Series connection. (*b*) Parallel connection. (*c*) Series/parallel connection. (*d*) Switched connection.



Redundant W/TA configuration in HPA of a 6/4 GHz bent pipe transponder.

The parallel connection of two TWTs as shown above raises the reliability of the amplifier stage to 0.60 at the mean time before failure(MTBF) period, assuming zero probability of a short circuit. A life tin=me of 50,000h is approximately 6 years of continuous operation, which is close to the typical design life time os a satellite. To further improve the reliability of the transponder, a second redundant transponder may be provided with switching between the two systems. Note that a combination of parallel and switched redundancy is used to combat failures that are catastrophic to one transponder channel and to the complete communication system.

References

1. www.wikipedia.com
2. http://www.tech-faq.com/vsat.html
3. M. Richharia, Mobile Satellite Communication: Principles and Trends, Pearson Education
4. Rappaort, Wireless Communications Principals and Practices
5. YI Bing Lin , Wireless and Mobile Network Architectures, John Wiley
6. P. Nicopolitidis ,Wireless Networks, John Wiley
7. Satellite Communications Dennis Roddy 3rd edition, Mc-Graw Hill publication
8. Satellite communications-Timothy Pratt, Charles Bostian and Jeremy Allnutt, WSE, Wiley Publications, 2nd Edition,2003.

SATELLITE LINK

BASIC TRANSMISSION THEORY

The RF (or free space) segment of the satellite communications link is a critical element that impacts the design and performance of communications over the satellite. The basic communications link, shown in Figure 4.1, identifies the basic parameters of the link.

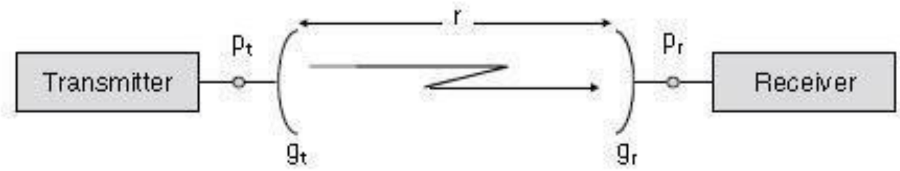


Figure 4.1 Basic communications link

The parameters of the link are defined as: pt = transmitted power (watts); pr = received power (watts); gt = transmit antenna gain; gr = receive antenna gain; and r = path distance (meters).

An electromagnetic wave, referred to as a ***radiowave*** at radio frequencies, is nominally defined in the range of ~100MHz to 100+GHz. The radiowave is characterized by variations of its electric and magnetic fields. The oscillating motion of the field intensities vibrating at a particular point in space at a frequency f excites similar vibrations at neighbouring points, and the radiowave is said to travel or to ***propagate***. The wavelength, λ, of the radiowave is the

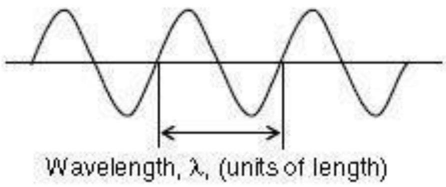


Figure 4.2 Definition of wavelength

spatial separation of two successive oscillations, which is the distance the wave travels during one cycle of oscillation (Figure 4.2).

The frequency and wavelength in free space are related by

$$\lambda = \frac{c}{f}$$

Where c is the phase velocity of light in a vacuum.

With c = 3×108 m/s, the free space wavelength for the frequency in GHz can be expressed as

$$\lambda(\text{cm}) = \frac{30}{f(\text{GHz})} \quad \text{or} \quad \lambda(\text{m}) = \frac{0.3}{f(\text{GHz})}$$

Consider a radiowave propagating in free space from a point source P of power pt watts. The wave is isotropic in space, i.e., spherically radiating from the point source P, as shown in Figure4.3

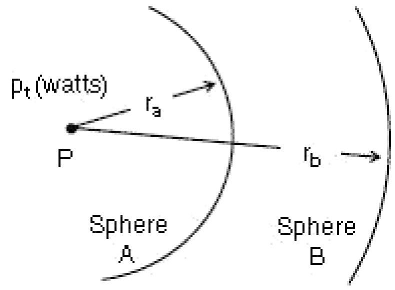


Figure 4.3 Inverse square law of radiation

The power flux density (or power density), over the surface of a sphere of radius ra from the point P, is given by

$$(pfd)_A = \frac{P_t}{4\pi r_a^2}, \text{ watts/m}^2$$

Similarly, at the surface B, the density over a sphere of radius rb is given by

$$(pfd)_B = \frac{P_t}{4\pi r_b^2}, \text{ watts/m}^2$$

The ratio of power densities is given by

$$\frac{(pfd)_A}{(pfd)_B} = \frac{r_b^2}{r_a^2}$$

Where (pfd)B < (pfd)A. This relationship demonstrates the well-known ***inverse square law of radiation***: the power density of a radiowave propagating from a source is inversely proportional to the square of the distance from the source.

Effective Isotropic Radiated Power

An important parameter in the evaluation of the RF link is the ***effective isotropic radiated power***, eirp. The eirp, using the parameters introduced in Figure 4.1, is defined as

eirp ≡ pt gt

or, in db, EIRP = Pt + Gt

The eirp serves as a single parameter 'figure of merit' for the transmit portion of the communications link.

Power Flux Density

The power density, usually expressed in watts/m2, at the distance r from the transmit antenna with a gain gt, is defined as the ***power flux density*** (pfd)r (see Figure 4.4).

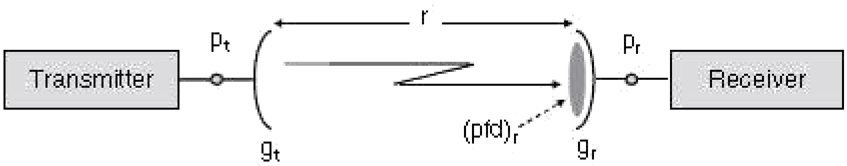


Figure 4.4 Power flux density

The (pfd)r is therefore

$$(pfd)_r = \frac{p_t\, g_t}{4\pi r^2}\ \text{w/m}^2$$

Or, in terms of the eirp,

$$(pfd)_r = \frac{eirp}{4\pi r^2}\ \text{w/m}^2$$

The power flux density expressed in dB, will be

$$(PFD)_r = 10\log\left(\frac{p_t\, g_t}{4\pi r^2}\right)$$

$$= 10\log(p_t) + 10\log(g_t) - 20\ \log(r) - 10\log(4\pi)$$

With r in meters,

$$(PFD)r = Pt + Gt - 20\ \log(r) - 10.99$$

Or

$$(PFD)r = EIRP - 20\ \log(r) - 10.99$$

Where Pt, Gt , and EIRP are the transmit power, transmit antenna gain, and effective radiated power, all expressed in dB.

The (pfd) is an important parameter in the evaluation of power requirements and interference levels for satellite communications networks.

Antenna Gain

Isotropic power radiation is usually not effective for satellite communications links, because the power density levels will be low for most applications (there are some exceptions, such as for mobile satellite networks, some directivity (gain) is desirable for both the transmit and receive antennas. Also, physical antennas are not perfect receptors/emitters, and this must be taken into account in defining the antenna gain.

Consider first a lossless (ideal) antenna with a physical aperture area of A(m2). The gain of the ideal antenna with a physical aperture area A is defined as

$$g_{ideal} \equiv \frac{4\pi A}{\lambda^2}$$

where λ is the wavelength of the radiowave.

Physical antennas are not ideal – some energy is reflected away by the structure, some energy is absorbed by lossy components (feeds, struts, subreflectors). To account for this, an ***effective aperture***, Ae, is defined in terms of an ***aperture efficiency***, η_A, such that

$$A_e = \eta_A A$$

Then, defining the 'real' or physical antenna gain as g,

$$g_{real} \equiv g = \frac{4\pi A_e}{\lambda^2}$$

Or,

$$g = \eta_A \frac{4\pi A}{\lambda^2}$$

Antenna gain in dB for satellite applications is usually expressed as the dB value above the gain of an isotropic radiator, written as 'dBi'. Therefore,

$$G = 10 \log\left[\eta_A \frac{4\pi A}{\lambda^2}\right], \text{dBi}$$

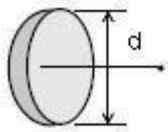
Note also that the effective aperture can be expressed as

$$A_e = \frac{g\lambda^2}{4\pi}$$

The aperture efficiency for a circular parabolic antenna typically runs about 0.55 (55 %), while values of 70% and higher are available for high performance antenna systems.

Circular Parabolic Reflector Antenna

The circular parabolic reflector is the most common type of antenna used for satellite earth station and spacecraft antennas. It is easy to construct, and has good gain and beamwidth characteristics for a large range of applications. The physical area of the aperture of a circular parabolic aperture is given by



$$A = \frac{\pi d^2}{4}$$

where d is the physical diameter of the antenna.

From the antenna gain Equation

$$g = \eta_A \frac{4\pi A}{\lambda^2} = \eta_A \frac{4\pi}{\lambda^2}\left(\frac{\pi d^2}{4}\right)$$

or

$$g = \eta_A \left(\frac{\pi d}{\lambda}\right)^2$$

Expressed in dB form,

$$G = 10 \log\left[\eta_A \left(\frac{\pi d}{\lambda}\right)^2\right] \quad \text{dBi}$$

For the antenna diameter d given in meters, and the frequency f in GHz,

$$g = \eta_A\,(10.472\ f\ d)^2$$

$$g = 109.66\,f^2\,d^2\,\eta_A$$

Or, in dBi

$$G = 10\ \log(109.66\,f^2\,d^2\,\eta_A)$$

Beamwidth

Figure 4.5 shows a typical directional antenna pattern for a circular parabolic reflector antenna, along with several parameters used to define the antenna performance. The ***boresight*** direction refers to the direction of maximum gain, for which the value g is determined from the above equations. The 1/2 ***power beamwidth*** (sometimes referred to as the '3 dB beamwidth') is the contained conical angle θ for which the gain has dropped to 1/2 the value at boresight, i.e., the power is 3 dB down from the boresight gain value.

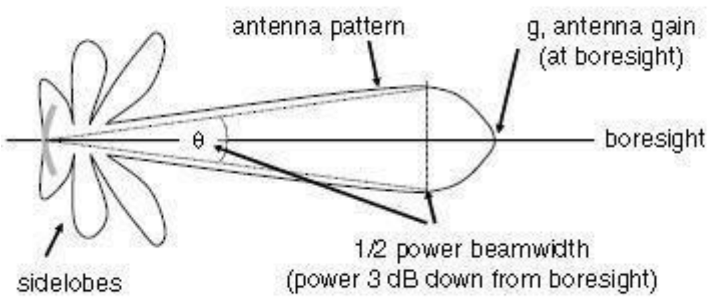


Figure 4.5 Antenna beamwidth

The antenna pattern shows the gain as a function of the distance from the boresight direction. Most antennas have ***sidelobes***, or regions where the gain may increase due to physical structure elements or the characteristics of the antenna design. It is also possible that some energy may be present behind the physical antenna reflector. Sidelobes are a concern as a possible source for noise and interference, particularly for satellite ground antennas located near to other antennas or sources of power in the same frequency band as the satellite link.

The antenna beamwidth for a parabolic reflector antenna can be approximately determined from the following simple relationship,

$$\theta \cong 75\frac{\lambda}{d} = \frac{22.5}{d\,f}$$

Where θ is the 1/2 power beamwidth in degrees, d is the antenna diameter in meters, and f is the frequency in GHz. Antenna beamwidths for satellite links tend to be very small, in most cases much less than 1◦, requiring careful antenna pointing and control to maintain the link.

Free-Space Path Loss

Consider now a receiver with an antenna of gain gr located a distance r from a transmitter of pt watts and antenna gain gt, as shown in Figure 4.4. The power pr intercepted by the receiving antenna will be

$$p_r = (pfd)_r A_e = \frac{p_t g_t}{4\pi r^2} A_e, \text{ watts}$$

Where (pfd)r is the power flux density at the receiver and Ae is the effective area of the receiver antenna, in square meters. Replacing Ae with the representation

$$p_r = \frac{p_t g_t}{4\pi d^2} \frac{g_r \lambda^2}{4\pi}$$

A rearranging of terms describes the interrelationship of several parameters used in link analysis:

$$p_r = \left[\frac{p_t g_t}{4\pi r^2}\right] g_r \left[\frac{\lambda^2}{4\pi}\right]$$

⇧	⇧
Power Flux Density	**Spreading Loss**
(pfd)	s
in w/m^2	in m^2

Basic Link Equation for Received Power

We now have all the elements necessary to define the basic link equation for determining the received power at the receiver antenna terminals for a satellite communications link. We refer again to the basic communications link (Figure 4.1, repeated here as Figure 4.6).

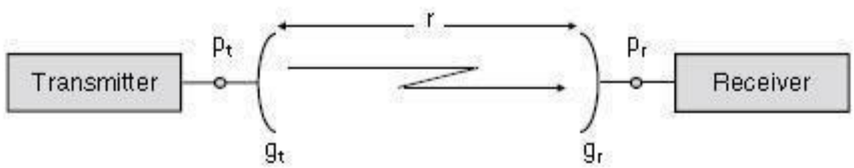


Figure 4.6 Basic communications link

The parameters of the link are defined as: pt = transmitted power (watts); pr = received power (watts); gt = transmit antenna gain; gr = receive antenna gain; and r = path distance (meters or km).

The receiver power at the receive antenna terminals, pr , is given as

$$p_r = p_t\, g_t \left(\frac{1}{l_{FS}}\right) g_r$$
$$= eirp \left(\frac{1}{l_{FS}}\right) g_r$$

Or, expressed in dB,

$$P_r(dB) = EIRP + G_r - L_{FS}$$

This result gives the basic link equation, sometimes referred to as the ***Link Power Budget***

Equation, for a satellite communications link, and is the design equation from which satellite design and performance evaluations proceed.

SYSTEM NOISE TEMPERATURE AND G/T RATIO

Noise temperature:

Noise temperature is useful concept in communication receivers, since it provides a way of determining how much thermal noise is generated by active and passive devices in the receiving system. At microwave frequencies, a black body with a physical temperature, Tp degrees kelvin, generates electrical noise over a wide bandwidth. The noise power is given by

$$P_n = k\,T_p B_n$$

Where

k=Boltzmann's constant=1.39×10^{-23}J/K=-228.6dBW/K/Hz
Tp=Physical temperature of source in kelvin degrees
Bn=noise bandwidth in which the noise power is measured, in hertz

Pn is the available noise power (in watts) and will be delivered only to a load that is impedance matched to the noise source. The term kTp is a noise power spectral density, in watts per hertz.

We need a way to describe the noise produced by the components of a low noise receiver. This can conveniently be done by equating the components to a black body radiator with an equivalent noise temperature, Tn kelvins.

To determine the performance of a receiving system we need to be able to find the total thermal noise power against which the signal must be demodulated.

We do this by determining the system noise temperature, Ts. Ts is the noise temperature of a noise source, located at the input of a noiseless receiver, which gives the same noise power as the original receiver, measured at the output of the receiver and usually includes noise from the antenna.

If the overall end-to-end gain of the receiver is Grx and its narrowest bandwidth is Bn Hz, the noise power at the demodulator input is

$$P_{no} = kT_s B_n G_{rx} \text{ watts}$$

Where Grx is the gain of the receiver from RF input to demodulator input.

The noise power referred to the input of the receiver is Pn where

$$P_{no} = kT_s B_n \text{watts}$$

Let the antenna deliver a signal power Pr watts to the receiver RF input. The signal power at the demodulator input is PrGrx watts, representing the power contained in the carrier and sidebands after amplification and frequency conversion within the receiver. Hence, the carrier-to-noise ratio at the demodulator is given by

The gain of the receiver cancels out in above equation . So we can calculate C/N ratios for our receiving terminals at the antenna output port. This is convenient, because a link budget will find Pr at this point. Using a single parameter to encompass all of the sources of noise in receiving terminals is very useful because it replaces several sources of noise in the receiver by a single system noise temperature, Ts.

Calculation of system Noise Temperature

The above figure shows a simplified communication receiver with an RF amplifier and single frequency conversion, from its RF input to the IF output. This is the form used for all radio receivers with few exceptions, known as the superhet. The superhet receiver has three main subsystems: a front end (RF amplifier, mixer and local oscillator) an IF amplifier (IF amplifiers and filters), and a demodulator and baseband section.

The RF amplifier in a satellite communications receiver must generate as little noise as possible, so it is called a low noise amplifier or LNA. The mixer and local oscillator from a frequency conversion stage that downconverts the RF signal to a fixed intermediate frequency(IF), where the signal can be amplified and filtered accurately.

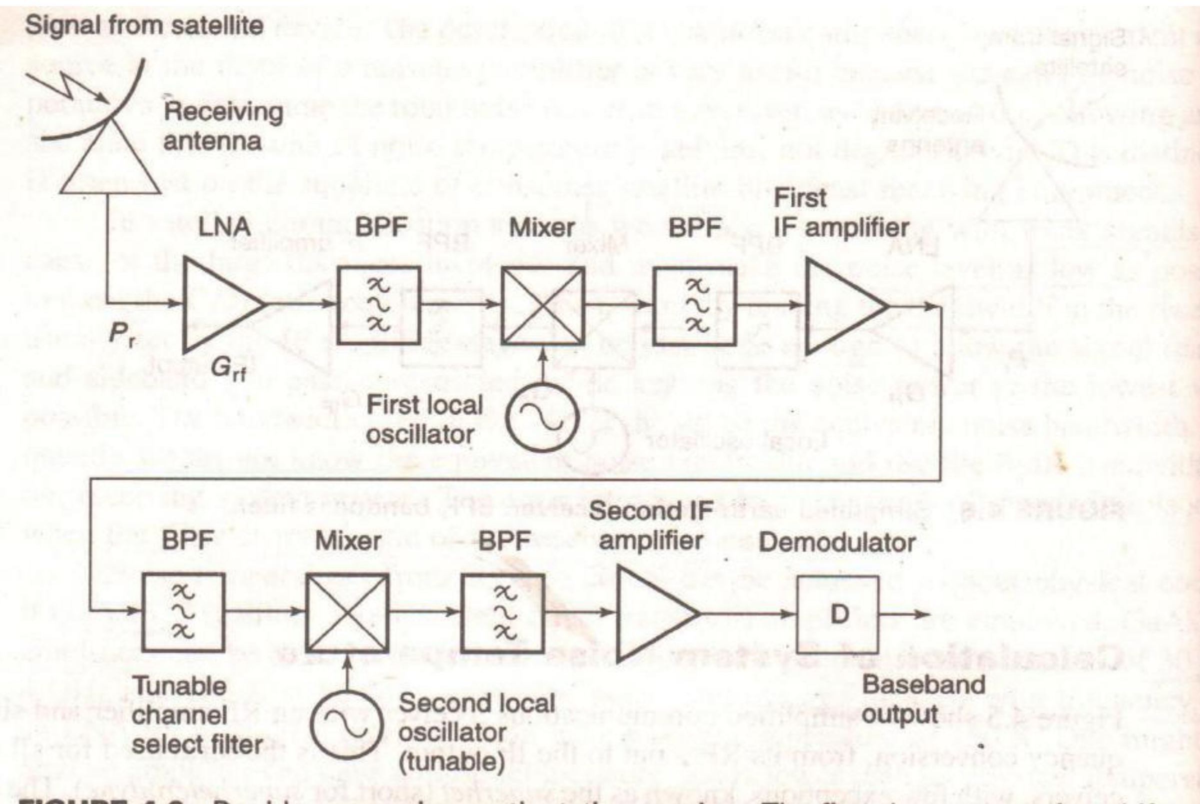
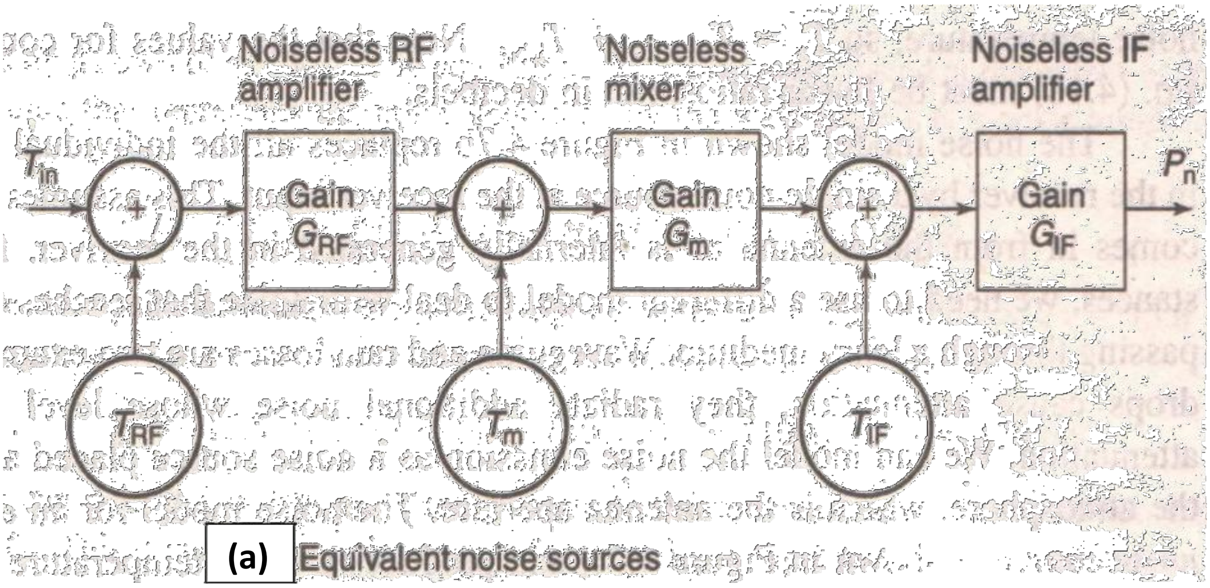


FIGURE 4.6 Double conversion earth station receiver. The first downconversion shifts signals in a 500-MHz band to the first IF range 900–1400 MHz. The second downconverter has a tunable local oscillator and channel selection filter to select the wanted transponder signal in the second IF centered at 70 MHz.



$$P_n = G_{IF} k T_{IF} B_n + G_{IF} G_m k T_m B_n + G_{IF} G_m G_{RF} k B_n (T_{RF} + T_{in})$$

Where G_{RF}, G_m and G_{IF} are the gains of the RF amplifier, mixer and IF amplifier, and T_{RF},T_m and T_{IF} are their equivalent noise temperatures. Tin is the noise temperature of the antenna, measured at its output port.

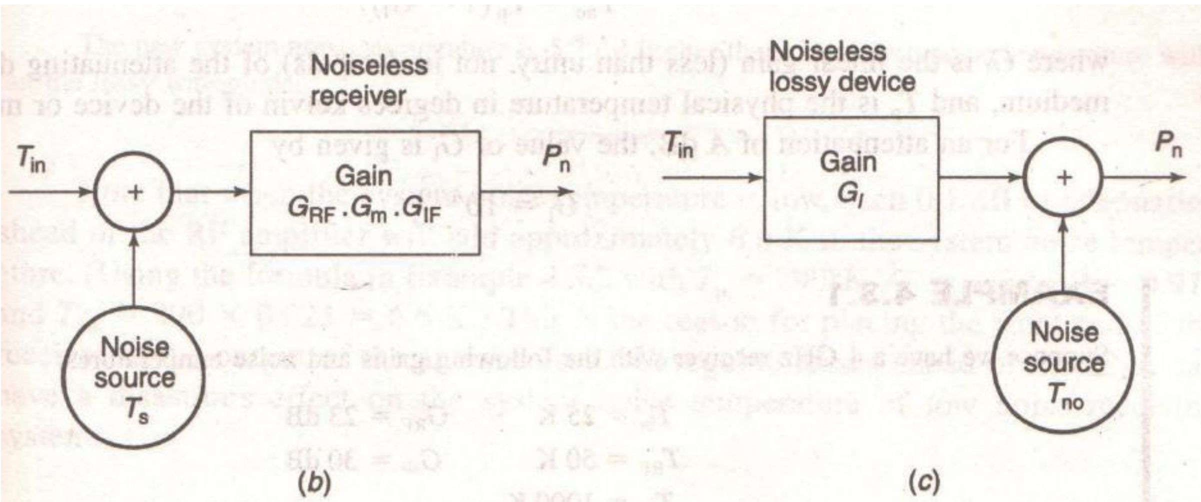


FIGURE 4.7 (*a*) Noise model of receiver. The noisy amplifiers and downconverter have been replaced by noiseless units, with equivalent noise generators at their inputs. (*b*) Noise model of receiver. All noisy units have been replaced by one noiseless amplifier, with a single noise source T_s as its input. (*c*) Noise model for a lossy device. The lossy device has been replaced by a lossless device, with a single noise source T_{no} at its output.

Above equation can be rewritten as

$$P_n = G_{IF}G_mG_{RF}\,[(kT_{IF}B_n)/(G_{RF}G_m) + (kT_mB_n)/G_{RF}+(T_{RF}+T_{in})]$$

- $G_{IF}G_mG_{RF}kB_n[T_{RF}+ T_{in} +T_m/G_{RF}+ T_{IF} /(G_{RF}G_m)]$

The single source of noise shown in figure(b) with noise temperature T_s generates the same noise power P_n at its output if

$$P_n= G_{IF}G_mG_{RF}\, kT_sB_n$$

The noise power at the output of the noise model in figure b will be the same as the noise power at the output of the noise model in fig (a) if

$$kT_sB_n= kB_n\,[(T_{in}+T_{RF}+T_m/G_{RF}+T_{IF}/G_mG_{RF})]$$

Hence the equivalent noised source in figure (b) has a system noise temperature T_s

where $Ts=[T_{in}+T_{RF}+T_m/G_{RF}+T_{IF}/(G_mG_{RF})]$

Succeeding gates of the receiver contribute less and less noise to the total system noise temperature. Frequently, when the RF amplifier in the receiver front end has high gain, the noise contributed by the IF amplifier and later stages can be ignored and the system noise temperature is simply the sum of the antenna noise and the LNA noise temperature, so

$$T_s=T_{antenna}+T_{LNA}.$$

Noise figure and noise source

Noise figure is frequently used to specify the noise generated within a device. The operational noise figure (N/F) is defined by the following formula:

Because noise temperature is more useful in satellite communication system, it is best to convert noise figure to noise temperature, Td. The relationship is

$$T=T0(\text{NF-1})$$

Where *To* is the reference temperature used to calculate the standard noise figure usually 290k.

G/T Ratio for Earth Stations

The link equation can be rewritten in terms of (C/N)at the earth station

Thus C/N α Gr/Ts and the terms in the square brackets are all constants for a given satellite system. The ratio Gr/Ts, which is usually quoted as simply G/T in decibels, with units db/k, can be used to specify the quality of a receiving earth station or a satellite receiving system, since increasing Gr/Ts increases C/N ratio.

DESIGN OF DOWNLINKS

The downlink of a satellite circuit is where the space craft is transmitting the data to the earth station and the earth station is receiving it.

Design of downlink: Link Budgets

C-band satellite parameters		
	Transponder saturated output power	20 W
	Antenna gain, on axis	20 dB
	Transponder bandwidth	36 MHz
	Downlink frequency band	3.7–4.2 GHz
Signal	FM-TV analog signal	
	FM-TV signal bandwidth	30 MHz
	Minimum permitted overall C/N in receiver	9.5 dB
Receiving C-band earth station		
	Downlink frequency	4.00 GHz
	Antenna gain, on axis, 4 GHz	49.7 dB
	Receiver IF bandwidth	27 MHz
	Receiving system noise temperature	75 K
Downlink power budget		
	P_t = Satellite transponder output power, 20 W	13.0 dBW
	B_o = Transponder output backoff	−2.0 dB
	G_t = Satellite antenna gain, on axis	20.0 dB
	G_r = Earth station antenna gain	49.7 dB
	L_p = Free space path loss at 4 GHz	−196.5 dB
	L_{ant} = Edge of beam loss for satellite antenna	−3.0 dB
	L_a = Clear air atmospheric loss	−0.2 dB
	L_m = Other losses	−0.5 dB
	P_r = Received power at earth station	−119.5 dBW
Downlink noise power budget in clear air		
	k = Boltzmann's constant	−228.6 dBW/K/Hz
	T_s = System noise temperature, 75 K	18.8 dBK
	B_n = Noise bandwidth, 27 MHz	74.3 dBHz
	N = Receiver noise power	−135.5 dBW
C/N ratio in receiver in clear air		

$$C/N = P_r - N = -119.5 \text{ dBW} - (-135.5 \text{ dBW}) = 16.0 \text{ dB}$$

C-band GEO Satellite link budget in rain

P_{rca}	= Received power at earth station in clear air	−119.5 dBW
A	= Rain attenuation	−1.0 dB
P_{rain}	= Received power at earth station in rain	−120.5 dBW
N_{ca}	= Receiver noise power in clear air	−135.5 dBW
ΔN_{rain}	= Increase in noise temperature due to rain	2.3 dB
N_{rain}	= Receiver noise power in rain	−133.2 dBW

C/N ratio in receiver in rain

$$C/N = P_{rain} - N_{rain} = -120.5 \text{ dBW} - (-133.2 \text{ dBW}) = 12.7 \text{ dB}$$

Satellite Link Design –Downlink Received Power

The calculation of carrier to noise ratio in a satellite link is based on equations for received signal power *P*r and receiver noise power:

Pr=EIRP+Gr-Lp-La-Lta-Lra dBW

Where:

EIRP =10log10(PtGt)dBW

Gr= 10log10 $(4\prod A_e/\lambda^2)$dB

Path Loss Lp = 10log10$[(4\prod R/\lambda)^2]$=20log10(4∏R/λ)dB

La= Attenuation in atmosphere

Lta= Losses associated with transmitting antenna

Lra= Losses associated with receiving antenna

Satellite Link Design: Down link Noise Power

A receiving terminal with a system noise temperature TsK and a noise bandwidth Bn HZ has a noise power Pn referred to the output terminals of the antenna where

$$P_n=k\ T_s B_n$$

The receiving system noise power is usually written in decibel units as

$$N=k+Ts+Bn\ dBW$$

Where

k=Boltzmann's constant=1.39×10^{-23}J/K= -228.6dBW/K/Hz Ts= the system noise temperature in dBK

Bn=noise bandwidth in which the noise power is measured, in hertz

UPLINK DESIGN

The uplink of a satellite circuit is where the earth station is transmitting the data to the space craft and the space craft is receiving it.

- Uplink design is easier than the down link in many cases
- Earth station could use higher power transmitters
- Earth station transmitter power is set by the power level required at the input of the transponder.
- Analysis of the uplink requires calculation of the power level at the input to the transponder so that uplink C/N ratio can be found
- With small-diameter earth stations, a higher power earth station transmitter is required to achieve a similar satellite EIRP.
- Uplink power control can be used to against uplink rain attenuation.

The noise power referred to the transponder input is N_{xp} w

$$N_{xp}= k + T_{xp} + B_n \text{ dBw}$$

The power received at the input of the transponder is P_{rxp}

$$P_{rxp}=P_t + G_t +G_r -L_p - L_{up} \text{ dBw}$$

The value of $(C/N)_{up}$ at the LNA input of the satellite receiver is given

$$\text{by } C/N = 10\log_{10}[p_r/(kT_sB_n)] = P_{rxp} - N_{xp} \text{ dB}$$

The received power at the transponder input is also given by

$$P_{rxp} = N + C/N \text{ dBw}$$

DESIGN OF SATELLITE LINKS FOR SPECIFIED C/N

- The BER or S/N ratio in the baseband channel of earth station receiver is determined by the ratio of the carrier power to the noise power in the IF amplifier at the input to the demodulator.
- When more than one C/N ratio is present in the link, we can add the individual C/N ratios reciprocally to obtain overall C/N ratio, which we will denote here as $(C/N)_0$. The overall $(C/N)_0$ ratio is what would be measured in the earth station at the output
of the IF amplifier

$$(C/N)_0=1/[1/ (C/N)_1+ 1/ (C/N)_2+ 1/ (C/N)_3+\ldots]$$

Overall $(C/N)_0$ with Uplink and Downlink Attenuation

- The effect of change in (C/N) ratio has a different impact on overall $(C/N)_0$ depending on the operating mode and gain of the transponder.
- There are three different transponder types or operating modes:

Linear transponder: $P_{out}= P_{in} + G_{xp}$ dBW

Nonlinear transponder: $P_{out}= P_{in} + G_{xp} - \Delta G$ dBW

Regenerative transponder: $P_{out}=$ Constant

Where P_{in} is the power delivered by the satellite's receiving antenna to the input of the transponder, P_{out} is the power delivered by the transponder HPA to the input of the satellite's transmitting antenna, G_{xp} is the gain of the transponder.

SYSTEM DESIGN EXAMPLE FOR KU-BAND COMMUNICATION LINK

System and Satellite Specification

Ku -band satellite parameters

Geostationary at 73^{o}W longitude. 28 Ku -band transponders

Total RF output power	2.24 kW
Antenna gain, on axis (transmit and receive)	31 dB
Receive system noise temperature	500 K
Transponder saturated output power: Ku band	80 W
Transponder bandwidth: Ku band	54 MHz

Signal: Compressed digital video signals with transmitted symbol rate of 43.2 Msps

Minimum permitted overall (C/N), in receiver	9.5 dB

Transmitting Ku-band earth station

Antenna diameter	5 m
Aperture efficiency	68%
Uplink frequency	14.15 GHz
Required C.,'N in Ku -band transponder	30 K
Transponder HPA output backoff	1 dB
Miscellaneous uplink losses	0.3 de
Location: -2 dB contour of satellite receiving antenna	

Receiving Ku -band earth station

Downlink frequency	11.45 GHz
Receiver IF noise bandwidth	43.2 MHz
Antenna noise temperature	30 K
LNA noise temperature	110 K
Required overall (C/N): in clear air	17 dB
Miscellaneous downlink losses	0.2 dB
Location: -3 dB contour of satellite transmitting antenna	

Rain attenuation and propagation factors

Ku -band clear air attenuation

Uplink	14.15 GHr	0.7 dB
Downlink	11.45 GH1	0.5 dB

Rain attenuation

Uplink	0.01% of year	6.0 dB
Downlink	0.01% of year	5.0 dB

Ku -Band Uplink Design

We must Find the uplink transmitter power required to achieve (C/N)up = 30 dB in clear air atmospheric conditions. We will first find the noise power in thc transponder for 43.2 MHz bandwidth, and then add 30 dB to find the transponder input power level.

Uplink Noise Power Budget

K=Boltzmann's constant	-228.6 dBW/K/Hz
Ts= 500K	27.0 dBK
B = 43.2 MHz	76.4 dBHz
N=transponder noise power	-125.2 dBW

The received power level at the transponder input must be 30 dB greater than the noise power.

Pr= power at transponder input = - 95.2 dBW

The uplink antenna has a diameter of 5 m and an aperture efficiency of 68%. At 14.15 GHz the wavelength is 2.120 cm = 0.0212 m. The antenna gain is

$$Gt = 10 \log[0.68 \times (\prod D/\lambda)2] = 55.7 \text{ dB}$$

The free space path loss is $Lp = 10 \log [(4\prod R/ \lambda)2] = 207.2$ dB

Uplink Power Budget

Pt=Earth station transmitter power	Pt dBW
Gt=Earth station antenna gain	55.7 dB
Gr=Satellite antenna gain	31.0 dB
Lp= Free space path loss	-207.2 dB
Lant= E/S on 2 dB contour	-2.0 dB
Lm = Other losses	-1.0 dB
Pr=Received power at transponder	Pt - 123.5 dB

The required power at the transponder input to meet the (C/N)up = 30 dB objective is -95.2dBW. Hence

$$Pt - 123.5 \text{ dB} = -95.2 \text{ dBW}$$
$$Pt = 28.3 \text{ dBW or } 675\text{W}$$

This is a relatively high transmit power so we would probably want to increase the transmitting antenna diameter to increase its gain, allowing a reduction in transmitter power.

Ku -Band Downlink Design

The first step is to calculate the downlink (C/N)dn that will provide (C/N)o=17dB Where (C/N)up= 30 dB.

$$1/(C/N)dn=1/(C/N)0-1/(C/N)up \text{ (not in dB)}$$

Thus

$$1/(C/N)dn = 1/50 - 1/1000 = 0.019$$
$$(C/N)dn = 52.6=17.2 \text{ dB}$$

We must find the required receiver input power to give (C/N)dn = 17.2 dB and then find the receiving antenna gain, Gr.

Downlink Noise Power Budget

K = Boltzmann's constant	-228.6 dB W/K/Hz
Ts = 30 +110 K = 140K	21.5 dBK
Bn= 43.2 MHz	76.4 dBHz
N= transponder noise power	-130.7 dBW

The power level at the earth station receiver input must be 17.2 dB greater than the noise power in clear air.

Pr =power at earth station receiver input =-130.7 dBW +17.2 dB = -113.5dBW

We need to calculate the path loss at 11.45 GHz. At 14.15 GHz path loss was 207.2dB. At 11.45 GHz path loss is

$$Lp= 207.2 - 20 \log10 (14.15/11.45) = 205.4 \text{ dB}$$

The transponder is operated with 1 dB output backoff, so the output power is 1 dB below 80W (80W=19.0 dBW).

$$Pt = 19 \text{ dBW} - 1 \text{ dB} = 18 \text{ dBW}.$$

Downlink Power Budget

P_t = Satellite transponder output power	18.0 dBW
G_t = Satellite antenna gain	31.0 dB
G_r = Earth station antenna gain	G_r dB
L_p = Free space path loss	-205.4 dB
L_a= E/S on -3 dB contour of satellite antenna	-3.0 dB
L_m= Other losses	-0.8 dB
P_r= Received power at transponder	G_r - 160.2 dB

The required power into the earth station receiver to meet the $(C/N)_{dn}$ = 17.2 dB objective is P_r = - 120.1 dBW. Hence the receiving antenna must have a gain G_r,where

$$G_r - 160.2 \text{ dB} = -113.5 \text{ dBW}$$

$$G_r = 46.7 \text{ dB or } 46{,}774 \text{ as a ratio}$$

The earth station antenna diameter, D, is calculated from the formula for antenna gain. G, with a circular aperture

$$G_r=0.65X(\prod D/\lambda)^2 =46{,}744$$

At 11.45GHz, the wavelength is 2.62cm=0.0262 m.Evaluating the above equation to find D gives the required receiving antenna diameter as D=2.14m.

UNIT III
Propagation Effects

Modulation and Multiplexing: Voice, Data, Video :

Communications satellites are used to carry telephone, video, and data signals, and can use both analog and digital modulation techniques.

Modulation:

Modification of a carrier's parameters (amplitude, frequency, phase, or a combination of them) in dependence on the symbol to be sent. **Multiplexing:**

Task of multiplexing is to assign space, time, frequency, and code to each communication channel with a minimum of interference and a maximum of medium utilization Communication channel refers to an association of sender(s) and receiver(s) that want to exchange data One of several constellations of a
carrier's parameters defined by the used modulation scheme.

Voice, Data, Video :

The modulation and multiplexing techniques that were used at this time were analog, adapted from the technology developed for The change to digital voice signals made it easier for long-distance.

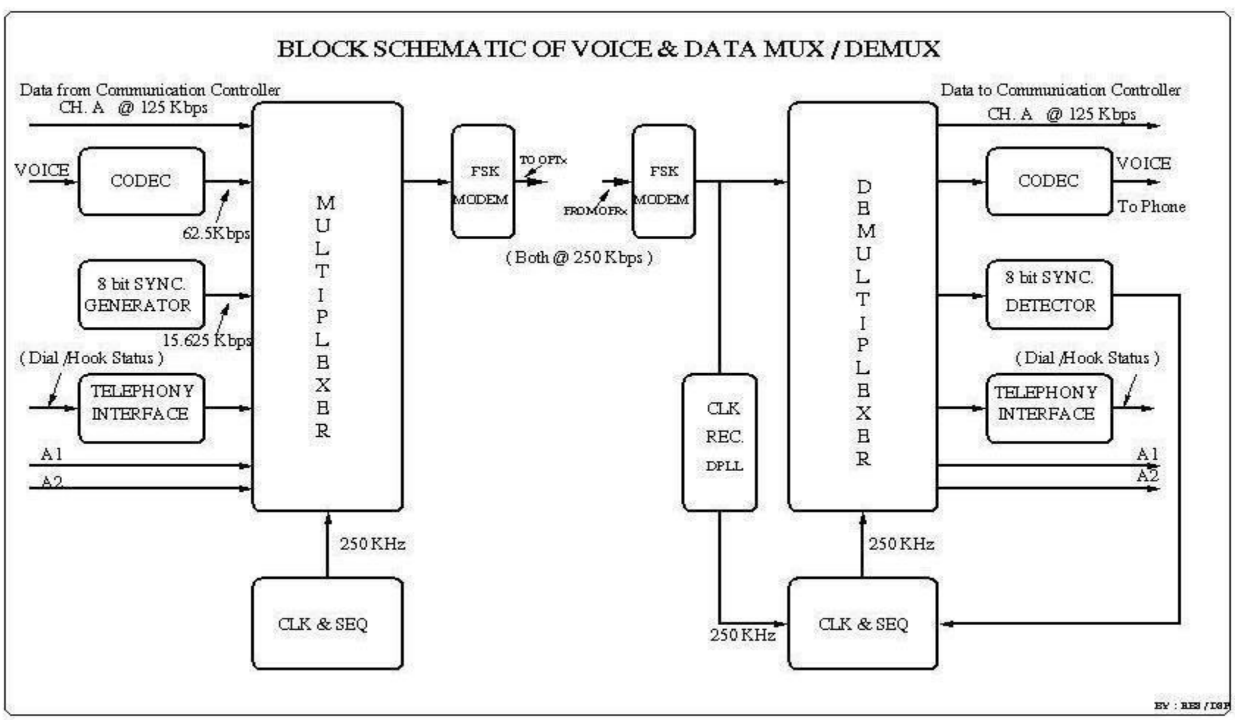


Figure 3.1 Modulation and Multiplexing: Voice/Data/Video

Communication carriers to mix digital data and telephone Fiber-optic Cable Transmission Standards System Bit rate (Mbps) 64- kbps Voice channel capacity Stuffing bits and words are added to the satellite data stream as needed to fill empty bit and word spaces.

Primarily for video provided that a satellite link's overall carrier-to-noise but in to older receiving equipment at System and Satellite Specification Ku-band satellite parameters.

Modulation And Multiplexing:

In analog television (TV) transmission by satellite, the baseband video signal and one or two audio subcarriers constitute a composite video signal.

Digital modulation is obviously the modulation of choice for transmitting digital data are digitized analog signals may conveniently share a channel with digital data, allowing a link to carry a varying mix of voice and data traffic.

Digital signals from different channels are interleaved for transmission through time division multiplexing TDM carry any type of traffic â€” the bent pipe transponder that can carry voice, video, or data as the marketplace demands.

Hybrid multiple access schemes can use time division multiplexing of baseband channels which are then modulate.

Analog – digital transmission system :

Analog vs. Digital Transmission:

Compare at two levels:

1. Data—continuous (audio) vs. discrete (text)
2. Signaling—continuously varying electromagnetic wave vs. sequence of voltage pulses.

Also Transmission—transmit without regard to signal content vs. being concerned with signal content. Difference in how attenuation is handled, but not focus on this.Seeing a shift towards digital transmission despite large analog base. Why?

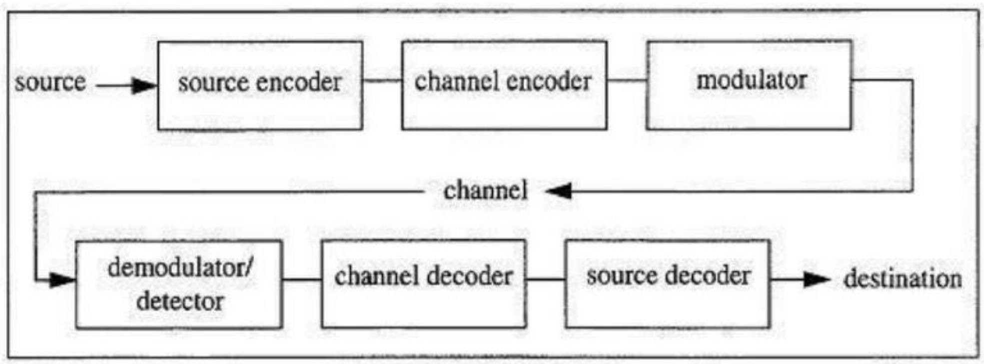


Figure 3.2 basic communication systems

- Improving digital technology
- Data integrity. Repeaters take out cumulative problems in transmission. Can thus transmit longer distances.
- Easier to multiplex large channel capacities with digital
- Easy to apply encryption to digital data
- Better integration if all signals are in one form. Can integrate voice, video and digital data.

Digital Data/Analog Signals:

Must convert digital data to analog signal such device is a modem to translate between bit-serial and modulated carrier signals?

To send digital data using analog technology, the sender generates a carrier signal at some continuous tone (e.g. 1-2 kHz in phone circuits) that looks like a sine wave. The following techniques are used to encode digital data into analog signals.

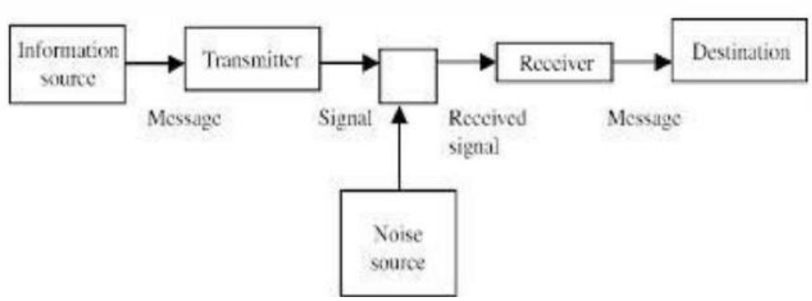


Figure 3.3 Digital /Analog Transmitter & receiver

Resulting bandwidth is centered on the carrier frequency.

- Amplitude-shift modulation (keying): vary the amplitude (e.g. voltage) of the signal. Used to transmit digital data over optical fiber.
- Frequency-shift modulation: two (or more tones) are used, which are near the carrier frequency. Used in a full-duplex modem (signals in both directions).

- Phase-shift modulation: systematically shift the carrier wave at uniformly spaced intervals.

For instance, the wave could be shifted by 45, 135, 225, 315 degree at each timing mark. In this case, each timing interval carries 2 bits of information.

Why not shift by 0, 90, 180, 270? Shifting zero degrees means no shift, and an extended set of no shifts leads to clock synchronization difficulties.

Frequency division multiplexing (FDM): Divide the frequency spectrum into smaller subchannels, giving each user exclusive use of a subchannel (e.g., radio and TV). One problem with FDM is that a user is given all of the frequency to use, and if the user has no data to send, bandwidth is wasted — it cannot be used by another user.

Time division multiplexing (TDM): Use time slicing to give each user the full bandwidth, but for only a fraction of a second at a time (analogous to time sharing in operating systems). Again, if the user doesn't have data to sent during his timeslice, the bandwidth is not used (e.g., wasted).

Statistical multiplexing: Allocate bandwidth to arriving packets on demand. This leads to the most efficient use of channel bandwidth because it only carries useful data.That is, channel bandwidth is allocated to packets that are waiting for transmission, and a user generating no packets doesn't use any of the channel resources.

Digital Video Broadcasting (DVB):

- Digital Video Broadcasting (DVB) has become the synonym for digital television and for data broadcasting world-wide.

- DVB services have recently been introduced in Europe, in North- and South America, in Asia, Africa and Australia.

- This article aims at describing what DVB is all about and at introducing some of the technical background of a technology that makes possible the broadcasting.

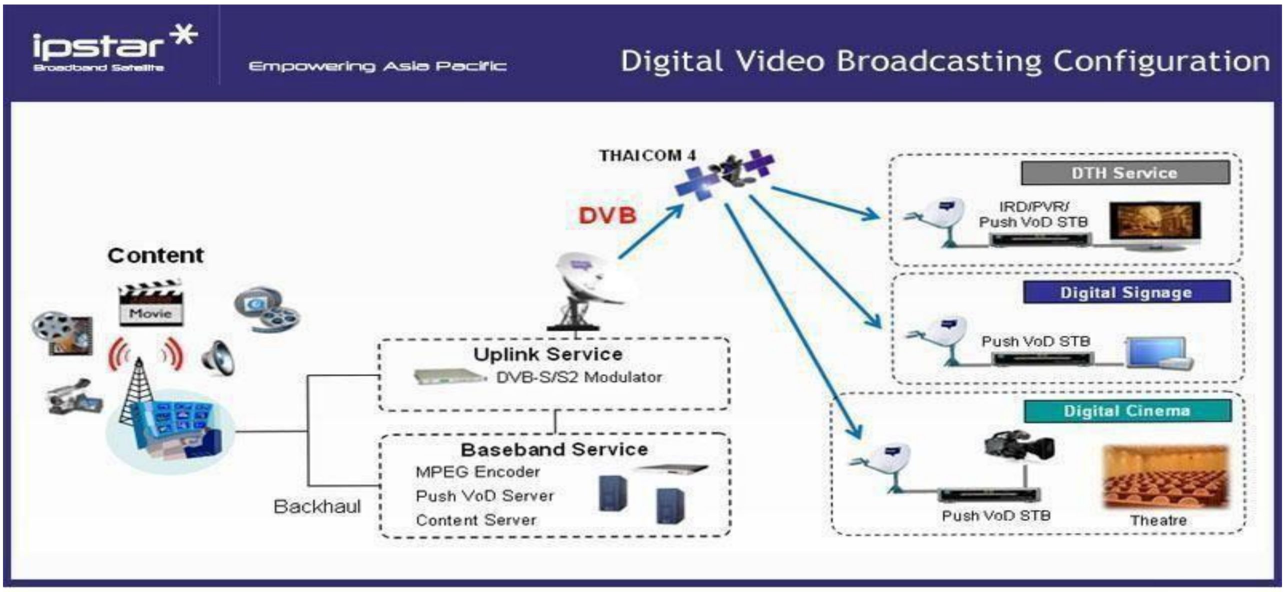


Figure 3.4 Digital Video Broadcasting systems

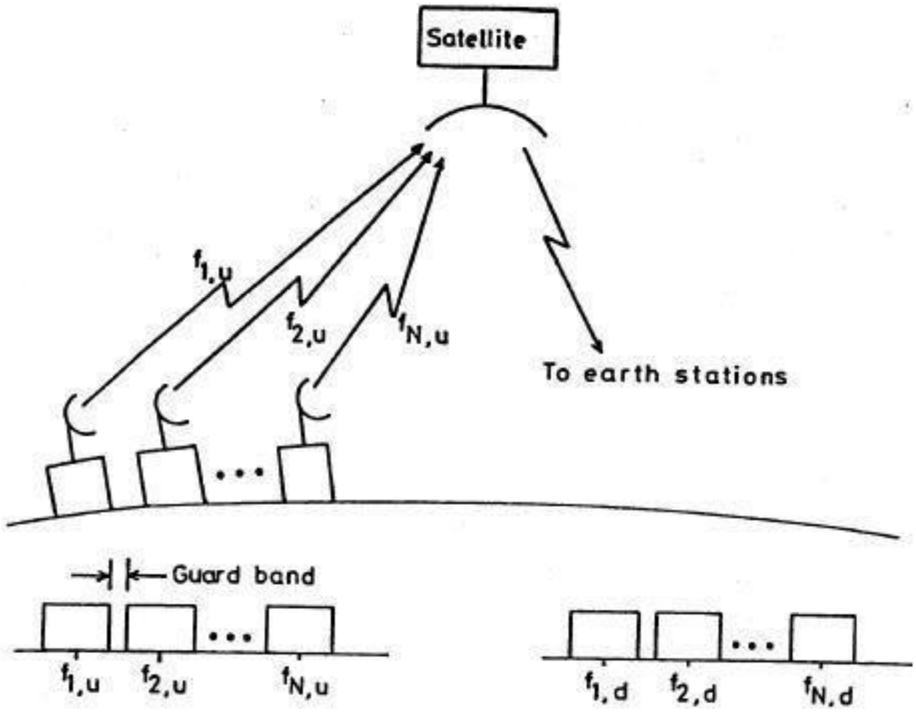
MULTIPLE ACCESS

With the increase of channel demands and the number of earth stations, efficient use of a satellite transponder in conjunction with many stations has resulted in the development of multiple access techniques. Multiple access is a technique in which the satellite resource (bandwidth or time) is divided into a number of nonoverlapping segments and each segment is allocated exclusively to each of the large number of earth stations who seek to communicate with each other. There are three known multiple access techniques. They are:

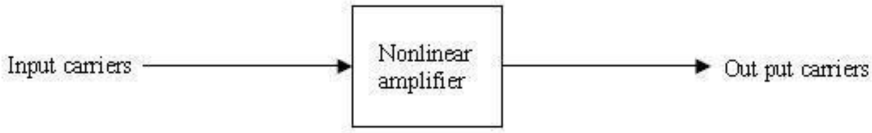
(1) Frequency Division Multiple Access (FDMA)
(2) Time Division Multiple Access (TDMA)
(3) Code Division Multiple Access (CDMA)

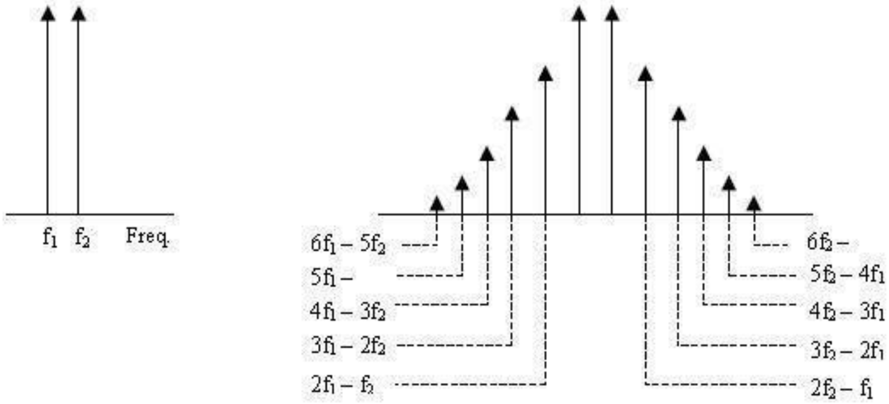
FREQUENCY DIVISION MULTIPLE ACCESS (FDMA)

The most widely used of the multiple access techniques is FDMA. In FDMA, the available satellite bandwidth is divided into portions of non-overlapping frequency slots which are assigned exclusively to individual earth stations. A basic diagram of an FDMA satellite system is shown in Fig.



Examples of this technique are FDM/FM/FDMA used in INTELSAT II & III and SCPC satellite systems. Also, SPACE (signal-channel-per-carrier PCM multiple access demand assignment equipment) used in INTELSAT IV in which channels are assigned on demand to earth stations is considered as a FDMA system. In FDMA systems, multiple signals from the same or different earth stations with different carrier frequencies are simultaneously passed through a satellite transponder. Because of the nonlinear mode of the transponder, FDMA signals interact with each other causing intermodulation products (intermodulation noise) which are signals at all combinations of sum and difference frequencies as shown in the example given in Fig.





The power of these intermodulation products represents a loss in the desired signal power. In addition, if these intermodulation products appear within the bandwidth of the other signals, they act as interference for these signals and as a result the BER performances will be degraded. The other major disadvantage of the FDMA system is the need for accurate uplink power control among network stations in order to mitigate the weak signal suppression effect caused by disproportionate power sharing of the transponder power.

Intermodulation

Intermodulation products are generated whenever more than one signal is carried by nonlinear device. Sometimes filtering can be used to remove the IM products, but if they are within the bandwidth of the transponder they cannot be filtered out. The saturation characteristic of a transponder can be modeled by a cubic curve to illustrate the generation of third –order intermodulation. Third -order IM is important because third –order products often have frequencies close to the signals that generate the intermodulation, and are therefore likely to be within the transponder bandwidth. To illustrate the generation of third - order intermodulation products, we will model the nonlinear characteristic of the transponder HPA with a cubic voltage relationship and apply two unmodulated carriers at frequencies f1 and f2 at the input of the amplifier

$$V_{out} = AV_{in} + b(V_{in})^3 \quad \text{.......(1)}$$

where A >> b.

The amplifier input signal is

$$V_1 \cos\omega_1 t + V_2 \cos\omega_2 t \quad \text{.... (2)}$$

The amplifier output signal is

$$V_{out} = AV_{in} + b(V_{in})^3$$
$$= \underbrace{AV_1 \cos\omega_1 t + AV_2 \cos\omega_2 t}_{\text{linear term}} + \underbrace{b(V_1 \cos\omega_1 t + V_2 \cos\omega_2 t)^3}_{\text{cubic term}} \quad (6.3)$$

The linear term simply amplifies the input signal by a voltage gain A. The cubic term, which will be denoted as V_{3out}, can be expanded as

$$V_{3out} = (V_1 \cos\omega_1 t + V_2 \cos\omega_2 t)^3$$
$$= b[V_1^3 \cos^3\omega_1 t + V_2^3 \cos^3\omega_2 t +$$
$$2V_2^2 \cos^2\omega_2 t \times V_2 \cos\omega_2 t + 2V_2^2 \cos^2\omega_2 t \times V_1 \cos\omega_1 t] \quad (6.4)$$

The first two terms contain frequencies f_1, f_2, $3f_1$, and $3f_2$. The triple frequency components can be removed from the amplifier output with band-pass filters. The second two terms generate the third-order IM frequency components.

We can expand the cosine squared terms using the trig identity $\cos^2 x = \frac{1}{2}[\cos 2x + 1]$. Hence the IM terms of interest become

$$V_{IM} = bV_1^2 \times V_2[\cos\omega_2 t \times (\cos 2\omega_1 t + 1)] +$$
$$bV_2^2 \times V_1[\cos\omega_1 t \times (\cos 2\omega_2 t + 1)]$$
$$= bV_1^2 \times V_2[\cos\omega_2 t \cos 2\omega_1 t + \cos\omega_2 t] +$$
$$bV_2^2 \times V_1[\cos\omega_1 t \cos 2\omega_2 t + \cos\omega_1 t] \quad (6.5)$$

The terms at frequencies f_1 and f_2 add to the wanted output of the amplifier, so the third-order intermodulation products are generated by the $f_1 \times 2f_2$ and $f_2 \times 2f_1$ terms.

Using another trig identity

$$\cos x \cos y = \cos(x + y) + \cos(x - y)$$

The output of the amplifier contains IM frequency components given by

$$V'_{IM} = bV_1^2 \times V_2[\cos(2\omega_1 t + \omega_2 t) + \cos(2\omega_1 t - \omega_2 t)]$$
$$+ bV_2^2 \times V_1[\cos(2\omega_2 t + \omega_1 t) + \cos(2\omega_2 t - \omega_1 t)] \quad (6.6)$$

We can filter out the sum terms in Eq. (6.6), but the difference terms, with frequencies $2f_1 - f_2$ and $2f_2 - f_1$ may fall within the transponder bandwidth. These two terms are known as the third-order intermodulation products of the high-power amplifier, because they are the only ones likely to be present at the output of a transponder which incorporates a narrow bandpass filter at its output. Thus the third-order intermodulation products that are of concern are given by V_{3IM} where

$$V_{3IM} = bV_1^2 V_2 \cos(2\omega_1 t - \omega_2 t) + bV_2^2 V_1 \cos(2\omega_2 t - \omega_1 t) \quad (6.7)$$

The magnitude of the IM products depends on the parameter b, which describes the nonlinearity of the transponder, and the magnitude of the signals. The wanted signals at the transponder output, at frequencies f_1 and f_2, have magnitudes AV_1 and AV_2. The wanted output from the amplifier is

$$V_{out} = AV_1 \cos\omega_1 t + AV_2 \cos\omega_2 t$$

The total power of the wanted output from the HPA, referenced to a 1 ohm load, is therefore

$$P_{out} = \tfrac{1}{2}A^2V_1^2 + \tfrac{1}{2}A^2V_2^2 = A^2(P_1 + P_2)\ \text{W} \quad (6.8)$$

where P_1 and P_2 are the power levels of the wanted signals. The power of the IM products at the output of the HPA is

$$P_{IM} = 2 \times (\tfrac{1}{2}b^2V_1^6 + \tfrac{1}{2}b^2V_2^6) = b^2(P_1^3 + P_2^3)\ \text{W} \quad (6.9)$$

It can be seen that IM products increase in proportion to the cubes of the signal powers with power levels that depend on the ratio $(b/A)^2$. The greater the nonlinearity of the amplifier (larger b/A ratio), the larger the IM products.

Intermodulation Example

Consider the case of a 36 -MHz bandwidth C -band transponder which has an output spectrum for downlink signals in the frequency range 3705-3741 MHz. The transponder carries two unmodulated carriers at 3718 and 3728 MHz with equal magnitudes at the input to the HPA. Using Eq. (6.7), the output of the HPA will contain additional frequency components at frequencies

$$f31= (2 \times 3718 — 3728) = 3708 \text{ MHz}$$

$$f32= (2 \times 3728 — 3718) = 3738 \text{ MHz}$$

Both of the IM frequencies are within the transponder bandwidth and will there

be present in an earth station receiver that is set to the frequency of this transponder. magnitude of the IM products will depend on the ratio b/A, a measure of the nonlinearity of the HPA, and on the actual level of the two signals in the transponder.

Now consider the case where the two signals carry modulation which spreads signal energy into a bandwidth of 8 MHz around each carrier. Carrier 1 has frequencies 3714 to 3722 MHz and carrier 2 has frequencies 3726 to 3734 MHz. Denoting the band of frequencies occupied by the signals as f_{nlo} to f_{nhi}, the intermodulation products cover the frequency bands

$$(2f_{1lo}-f_{2hi}) \text{ to } (2f_{1hi}-2f_{2lo}) \text{ and } (2f_{2lo}-f_{1hi}) \text{ to } (2f_{2hi}-f_{1lo})$$

The IM products are spread over bandwidths (2B1+ B2) and (2B2+ B1). Hence the third -order IM products for this example cover these frequencies: 3706 — 3730 MHz and 3716 — 3740 MHz with bandwidths of 24 MHz.

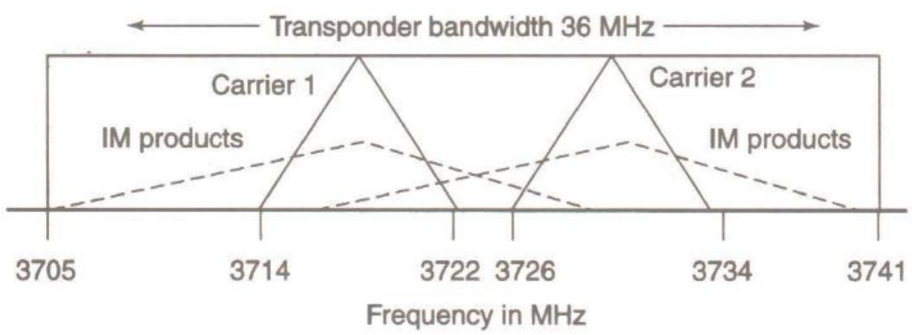


FIGURE 6.4Intermodulation between two C -band carriers in a transponder with third -order nonlinearity.

The location of the 8 MHz wide signals and 24 MHz wide IM products is illustrated in Figure 6.4. The intermodulation products now interfere with both signals, and also cover the empty frequency space in the transponder. Third -order IM products grow rapidly as the output of the transponder increases Toward saturation. Equation (6.9) shows that IM power increases as the cube of signal power in decibel units, every 10 dB increase in signal power causes a 30 dB increase in IM product-power. Consequently, the easiest way to reduce IM problems is to reduce the level of it the signals in the HPA. The output power of an operating transponder is related to its saturated output power by output backoff. Backoff is measured in decibel units, so a transponder with a 50W rated (saturated) output power operating with an output power of 25 W has output backoff of 17 dBW —14 dBW = 3 dB. Intermodulation products are reduced by 9 dB when 3 dB backoff is applied, so any nonlinear transponder carrying more than one signal will usually have some backoff applied. Since a transponder is an amplifier, the output power level is controlled by the input power, and there is a saturated input power level corresponding to the saturated output level. When the transponder is operated with output backoff, the power level at its input is reduced by the input backoff because the transponder characteristics are not linear, input backoff is always larger than output backoff. Figure 6.5 illustrates the operating point and input and output backoff for a transponder with a nonlinear TWTA. The nonlinearity of the transponder causes the input and output backoff values to be unequal. In the example shown in Figure 6.5, the transponder saturates at an input power of —100 dBW. The transponder is operated at an input power of —102.2 dBW, giving an input backoff of —2.2 dB. The corresponding output backoff is 1.0 dB, giving an output power of 16 dBW (40W), 10W below the saturated output power of 50W (17 dBW).

Note that the TWTA has slightly different characteristics when operated with a single carrier and multiple carriers. The generation of intermodulation products when multiple carriers are present robs the wanted output of some of the transponder output power. For the nonlinearity shown in Figure 6.5, the reduction in output power is 0.6 dB at saturation. In the example above, both carriers had equal power. If the powers are unequal, the weaker signal may be swamped by intermodulation products from the stronger carrier. This can be seen from Eq.(6.9);the IM products that tend to affect Carrier 1 have voltages proportional to the square of the voltage of Carrier 2.

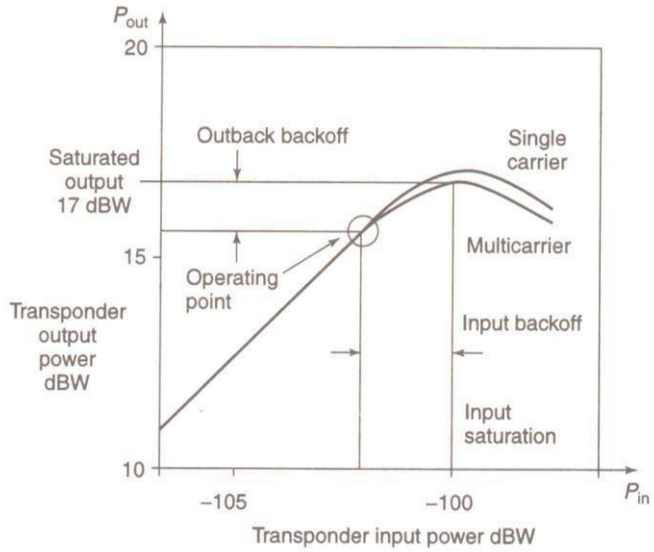


FIGURE 6.5 Typical input–ouput characteristic of a transponder using a traveling wave tube amplifier (TWTA). To maintain quasi-linear operation and minimize intermodulation problems with multiple carriers, the transponder must be operated below its saturated output power level. In this example, the saturated output power from the transponder is 50 W (17 dBW) with a single carrier. The saturated output power is slightly lower with multiple carriers because some output power is converted to intermodulation products.

Calculation of C/N with Intermodulation

Intermodulation between carriers in a nonlinear transponder adds unwanted products into the transponder bandwidth that are treated as though the interference were Gaussian noise For wideband carriers, the behavior of the IM products will be noiselike; with narrow band carriers, the assumption may not be accurate, but is applied because of the difficulty of determining the exact nature of the IM products.

The output backoff of a transponder reduces the output power level of all carriers, which therefore reduces the (C/N) ratio in the transponder. The transponder C/N ratio appears as (C/N)up in the calculation of the overall (C/N)0 ratio in the earth station receiver 1M noise in the transponder is defined by another C/N ratio, (C/N), Which enters the overall (C/N)0 ratio through the reciprocal formula (using linear C/N power ratios)

$$(C/N)_0 = 1/[1/(C/N)_{up} + 1/(C/N)_{dn} + 1/(C/N)_{IM}$$

Techniques for the calculation of $(C/N)_{IM}$ are beyond the scope of this text. Full knowledge of the transponder nonlinearity and the signals carried by the transponder is required to permit (C/N)IM to be calculated. There is an optimum output backoff for any nonlinear transponder operating in FDMA mode. Figure 6.6 illustrates the effect of the HPA operating point on each C/N ratio in Eq. (6.10) when the operating point is set by the power transmitted by the uplink earth station. The uplink (C/N)up ratio increases linearly as the transponder input power is increased, leading to a corresponding nonlinear increase in transponder output power as the nonlinear region of the transponder is reached, the downlink (C/N)dn ratio increases less rapidly than (C/N)up because the nonlinear transponder is going into saturation Intermodulation products start to appear as the nonlinear region is approached, increasing rapidly as saturation is reached. With a third -order model for nonlinearity, the intermodulation products increase in power at three times the rate at which the input power to the transponder is increases, causing (C/N)IM to decrease rapidly as saturation is approached. When all three C/N ratios are combined through Eq. (6.10), the overall (C/N)0 ratio in the receiving earth station receiver has a maximum value at an input power level of —104 dBW in the example in Figure 6.6. This is the optimum operating point for the transponder. The optimum operating point may be many decibels below the saturated output level of the transponder under some conditions.

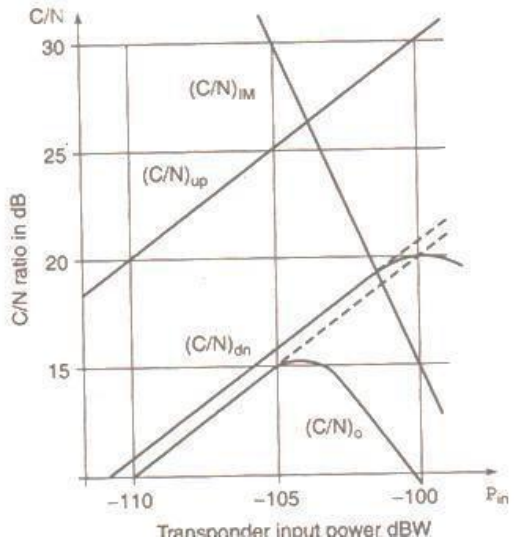
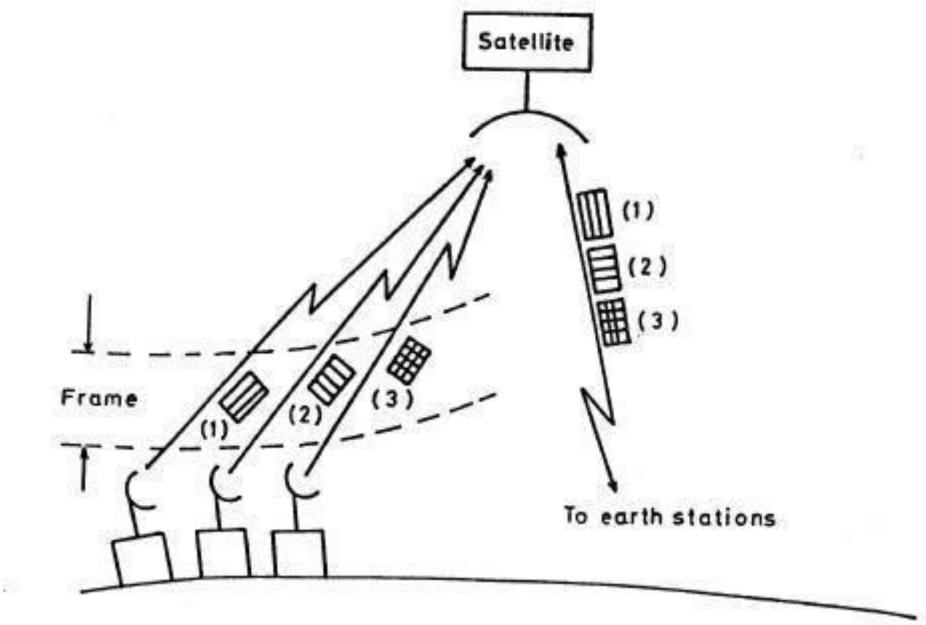


FIGURE 6.6 C/N ratios for a link using the nonlinear transponder illustrated in Figure 6.5. Overall $(C/N)_0$ at the receiving earth station is the combination of the three C/N ratios shown in this figure. As the power level at the input of the transponder is increased, $(C/N)_{up}$ in the transponder increases linearly, but $(C/N)_{dn}$ in the earth station receiver increases less rapidly as the transponder saturates. Third-order intermodulation products are generated in the transponder as it saturates, causing overall $(C/N)_0$ to peak at an input level of −104 dBW. This is the optimum operating point for this transponder. The dashed lines show C/N ratios for a transponder that does not saturate.

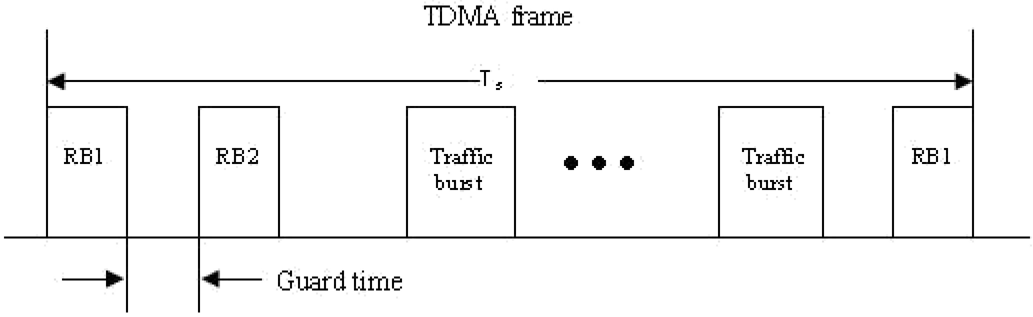
VSAT networks and mobile satellite telephones often use single channel per carrier (SCPC) FDMA to share transponder bandwidth. Because the carriers are narrowband, in the 10 to 128 kHz range typically, a 36 or 54 MHz transponder may carry many hundreds of carriers simultaneously. The balance between the power levels of the carriers may not be maintained, especially in a system with mobile transmitters that can be subject to fading. The transponder must operate in a linear mode for such systems to be feasible, either by the use of a linear transponder or by applying large output backoff to force operation of the transponder into its linear region.

TIME DIVISION MULTIPLE ACCESS (TDMA)

In search of an alternative multiple access technique; attention was focused on the possibilities afforded by TDMA. In TDMA, the sharing of the communication resource by several earth stations is performed by assigning a short time (time slot) to each earth station in which they have exclusive use of the entire transponder bandwidth and communicate with each other by means of non-overlapping burst of signals. A basic TDMA system is shown in Fig.



In TDMA, the transmit timing of the bursts is accurately synchronized so that the transponder receives one burst at a time. Each earth station receives an entire burst stream and extracts the bursts intended for it. A frame consists of a number of bursts originating from a community of earth stations in a network. A TDMA frame structure is shown in Fig.

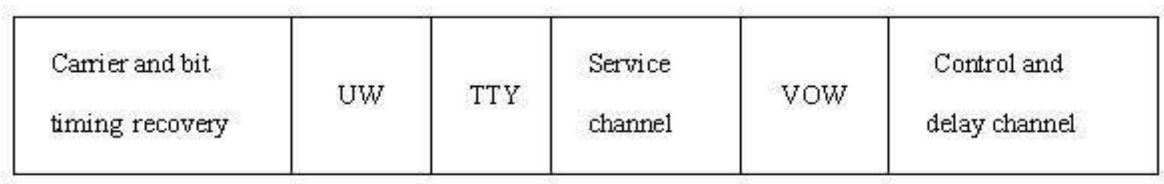


It consists of two reference bursts RB1and RB2, traffic bursts and the guard time between bursts. As can be seen, each TDMA frame has two reference bursts RB1 and RB2. The primary reference burst (PRB), which can be either RB1 or RB2, is transmitted by one of the earth stations in the network designated as the primary reference earth station. For reliability, a second reference burst (SRB) is transmitted by a secondary reference earth station. To ensure undisrupted service for the TDMA network, automatic switchover between these two reference stations is provided. The reference bursts carry no traffic information and are used to provide synchronization for all earth stations in the network.

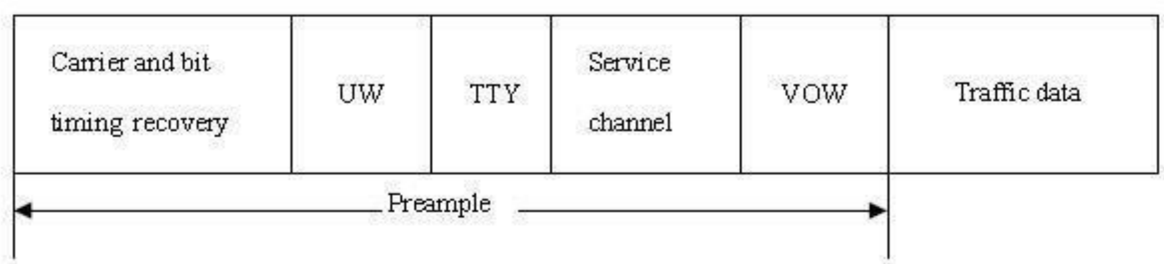
The traffic bursts carry information from the traffic earth station. Each earth station accessing a transponder may transmit one or two traffic bursts per TDMA frame and may position them anywhere in the frame according to a burst time plan that coordinates traffic between earth stations in the network.

The Guard time between bursts ensures that the bursts never overlap at the input to the transponder.

The TDMA bursts structure of the reference and traffic burst are given in Fig



Reference burst



Traffic burst

In the traffic burst, traffic data (information bits) is preceded by a pattern of bits referred to as a preamble which contains the information for synchronization, management and control. Various sequences in the reference burst and traffic burst are as follows:

Carrier and bit timing recovery (CBTR)

The CBTR pattern provides information for carrier and timing recovery circuits of the earth station demodulator. The length of the CBTR sequence depends on the carrier-to-noise ratio at the input of the demodulator and the acquisition range. For example, the 120 Mb/s TDMA system of INTELSAT V has a 48 symbol pattern for carrier recovery and a 128 symbol pattern for bit timing recovery.

Unique word (UW)

The unique word sequence in the reference burst provides the receive frame timing that allows an earth station to locate the position of a traffic burst in the frame. The UW in the traffic burst marks the beginning of the traffic burst and provides information to an earth station so that it selects only those traffic bursts intended for it. The UW is a sequence of ones and zeros selected to exhibit good correlation properties to enhance detection. The UW of the INTELSAT V TDMA system has a length of 24 symbols.

Teletype (TTY) and voice order wire (VOW)

Teletype and voice order wire patterns carry instructions to and from earth stations. The number of symbols for each of the patterns is 8 symbols for the INTELSAT V TDMA.

Service channel (SC)

The service channel of the reference burst carriers management instructions such as burst time plan which gives the coordination of traffic between earth stations, i.e. position, length, and source and destination earth stations corresponding to traffic bursts in the TDMA frame. The channel also carries monitoring and control information to the traffic stations.

The SC of the traffic burst carries the traffic station's status to the reference station (value of transmit delay used and reference station from which the delay is obtained). It also contains other information such as the high bit error rate and UW loss alarms to other traffic stations. The INTELSAT V TDMA has an 8-symbol SC for each of the bursts.

Control and delay channel (CDC)

The control and delay channel pattern carries acquisition and synchronization information to the traffic earth stations to enable them to adjust their transmit delays so that bursts arrive at the satellite transponder within the correct time slots in the frame. It also carries the reference station status code which enables them to identify the primary and secondary reference bursts. Eight symbols are allocated for this channel in the INTELSAT V TDMA.

Traffic data

This portion contains the information from a source traffic station to a destination traffic station. The informants can be voice, data, video or facsimile signals. The traffic data pattern is divided into blocks of data (referred to as subburst).

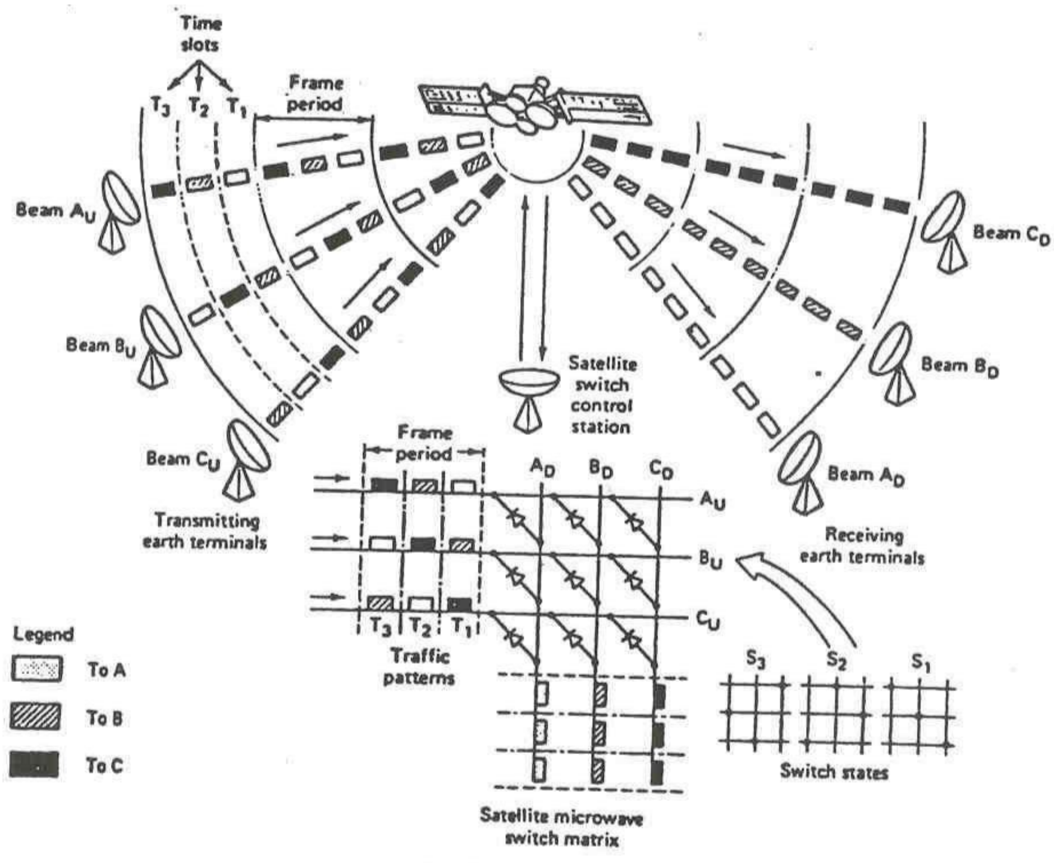
The size of each data block is given by:

Subburst size (symbols) = symbol rate (symbols/sec) X frame length (sec).

The INTELSAT TDMA with a frame length of $T f$ = 2 msec for PCM voice data has a subburst size of 64 symbols long.

Satellite-switched TDMA (SS-TDMA)

A satellite-switched TDMA system is an efficient TDMA system with multiple spot beam operation for the uplink and downlink transmissions. The interconnection between the uplink and downlink beams is performed by a high-speed switch matrix located at the heart of the satellite. An SS-TDMA scheme provides a full interconnection of TDMA signals among various coverage regions by means of interconnecting the corresponding uplink and downlink beams at a switching time. Figure shows a three-beam (beams A, B and C) example of a SS-TDMA system.



Satellite-switched TDMA (SS/TDMA).

The switch matrix is configured in a crossbar design in which only a single row is connected to a single column at a time. In this figure, three different traffic patterns during time slot intervals T1, T2 and T3, with three different switch states s1, s2 and s3 are also shown. The switching sequence is programmed via a ground control so that states can be changed from time to time. The advantages of SS-TDMA systems over TDMA systems are:

(1) The possibility of frequency re-use by spot-beam spatial discrimination, i.e. the same frequency band can be spatially re-used many times. Hence, a considerable increase in satellite capacity can be made.

(2) The use of a narrow antenna beam which provides a high gain for the coverage region. Hence, a power saving can be obtained in both the uplink and downlink. An SS-TDMA scheme has been planned for INTELSAT VI and Olympus satellites.

Satellite Switched TDMA

One advantage that TDMA has when used with a baseband processing transponder is satellite switched TDMA. Instead of using a single antenna beam to maintain continuous communication with its entire coverage zone, the satellite has a number of narrow antenna beams that -can be used sequentially to cover the zone. A narrow antenna beam has a high gain than a broad beam, which increases the satellite EIRP and therefore increases the capacity of the downlink. Uplink signals received by the satellite are demodulated to recover the bit streams, which are structured as a sequence of packets addressed to different receiving earth stations. The satellite creates TDMA frames of data that contain packets addressed to specific earth stations, and switches its transmit beam to the direction of the receiving earth station as the packets are transmitted. Note that control of the TDMA network timing could now be on board the satellite, rather than at a master earth station.

ONBOARD PROCESSING

The discussion of multiple access so far has assumed the use of a bent pipe transponder. which simply amplifies a signal received from earth and retransmits it back to earth at a different frequency. The advantage of a bent pipe transponder is flexibility. The transponder can be used for any combination of signals that will fit within its bandwidth. The disadvantage of the bent pipe transponder is that it is not well suited to uplinks from small earth stations, especially uplinks operating in Ka band. Consider a link between a same transmitting earth station and a large hub station via a bent pipe GEO satellite transponder. There will usually be a small rain fade margin on the uplink from the transmitting station because of its low EIRP. When rain affects the uplink, the C/N ratio in the transponder will fall. The overall C/N ratio in the hub station receiver cannot be greater than the C/N ratio in the transponder, so the bit error rate at the hub station will increase quickly as rain affects the uplink. The only available solution is to use forward error correction coding on the link, which lowers the data throughput but is actually needed for less than 5% of the time. The problem of uplink attenuation in rain is most severe for 30/20 GHz uplinks with small margins. Outages are likely to be frequent unless a large rain fade margin is included- in the uplink power budget. Onboard processing or a baseband processing transponder can overcome this problem by separating the uplink and downlink signals and their C/N ratios. The baseband processing transponder can also have different modulation schemes on the

uplink and downlink to improve spectral efficiency, and can dynamically apply forward error control to only those links affected by rain attenuation.
All LEO satellites providing mobile telephone service use onboard processing, and Ka-band satellites providing Internet access to individual users also use onboard processing.

Satellite Switched TDMA with Onboard Processing
Baseband processing is essential in satellites using satellite switched TDMA, because data packets must be routed to different antenna beams based on the address of the destination earth station. The data in such systems is always sent in packets which contain a header and a traffic section. The header contains the address of the originating station and the address of the destination earth station. When satellite switched TDMA is used, the transponder must extract the destination information and use it to select the correct downlink beam for that packet. The satellite is operating much like a router in a terrestrial data transmission system. Switched beam operation of an uplink from a small earth station is more difficult to achieve because it requires synchronization of the earth station transmit time with the satellite beam pointing sequence, in much the same way that a TDMA uplink operates. However, the uplink can operate in a small bandwidth which overcomes the chief disadvantage of classic TDMA—the requirement for high burst rate transmissions and high transmit power.

Satellite switched TDMA can greatly increase the throughput of a transponder. Consider, for example, a satellite providing Internet access to individual users in the United States. The uplink and downlink beams at the satellite must provide coverage over an area approximately 6° by 3°, as seen from the satellite. Antenna gain and beamwidth are related by the approximate relationship G = 33,000/(product of beamwidths in degrees).This limits the maximum achievable satellite antenna gain to approximately 32.5 dB.

A satellite with switched beam capability can have much narrower beams with higher gain than a satellite with a single fixed beam. The limitation on gain is the diameter of the antenna, which must fit inside the launch vehicle shroud. For launchers available in 2000, this limit is about 3.5 m. At 20 GHz, the uplink frequency for Ka band, an antenna with a circular aperture of diameter D = 3.5 m and aperture efficiency of ηA = 65% has a gain G = ηA(ΠD/A)2 = 55.4 dB, and its beamwidth is approximately 75 λ/D Degrees = 0.32°. The corresponding downlink antenna for 30 GHz that has a beamwidth of 0.32° and a gain of 55.4 dB has a diameter of 2.33 m. The switched beam satellite has an antenna gain almost 23 dB higher than the single beam satellite, which can be traded directly for reduction in uplink or downlink transmit power, and uplink downlink data rate. However, the satellite must generate at least 170 beams to cover of the United States with 0.32° beams, with a consequent increase in satellite antenna complexity.
Satellite switched TDMA and multiple beam antennas are a feature of most of proposed Ka - band Internet access satellites. The Astrolink satellites, for example, have 105 spot beams for links to small user terminals. The satellite uplink (30 GHz) antenna has a diameter of 2.5 m and the downlink antenna has a diameter of 3.25 m. There are five spot beams for links to hub stations; the large antennas used by the hub stations al- low a lower gain antenna with a broader beam to be used on the satellite. Coverage of the United States with multiple beams

is not always provided uniformly. Differences in population densities and the frequency of heavy rainfall make it advantageous to provide more system capacity to metropolitan areas, and also to provide higher link margins to areas with more frequent heavy rainfall, such as Florida and the south- eastern states. In the most sophisticated of large GEO satellites, a steerable phased array antenna can be used, with control of beam pointing from the ground via the satellite's telemetry and command link. The antenna beams can then be moved to provide coverage of areas with highest demand for traffic. The growth of the terrestrial optical fiber network will eventually fulfill the need for high-speed access to the Internet. Where direct access to an ISP is available via optical fiber, the transmission rate is likely to be higher and the cost to the user is likely to be lower. As the fiber network spreads through metropolitan areas, an Internet access satellite can concentrate its service on less well populated and rural areas. A steerable beam antenna allows the geographical capacity of the satellite to be reconfigured throughout its lifetime.

DEMAND ACCESS MULTIPLE ACCESS (DAMA)

Demand access can be used in any satellite communication link where traffic from an earth station is intermittent. An example is an LEO satellite system providing links to mobile telephones. Telephone voice users communicate at random times, for periods ranging from less than a minute to several minutes. As a percentage of total time, the use of an individual telephone may be as little as 1%. If each user were allocated a fixed channel, the utilization of the entire system might be as low as 1%, especially at night when demand for telephone channels is small. Demand access allows a satellite channel to be allocated to a user on demand, rather than continuously, which greatly increases the number of simultaneous users who can be served by the system. The two-way telephone channel may be a pair of frequency slots in a DA-SCPC system, a pair of time slots in a TDM or TDMA system, or any combination or FDMA, TDM, and TDMA. Most SCPC-FDMA systems use demand access to ensure that the available bandwidth in a transponder is used as fully as possible.

In the early days of satellite communication, the equipment required to allocate channels on demand, either in frequency or time, was large and expensive. The growth of cellular telephone systems has led to the development of low cost, highly integrated controllers and frequency synthesizers that make demand access feasible. Cellular telephone systems use demand access and techniques similar to those used by satellite systems in the allocation of channels to users. The major difference between a cellular system and a satellite system is that in a cellular system the controller is at the base station to which the user is connected by a single hop radio link. In a satellite communication system, there is always a two hop link via the satellite to a controller at the hub earth station. Controllers are not placed on the satellites largely because of the difficulties in determining which links are in use, and who will be charged for the connection.

As a result, all connections pass through a controlling earth station that can determine whether to permit the requested connection to be made, and who should be charged. In international satellite communication systems issues such as landing rights require the owner of the system to ensure that communication can take place only between users in preauthorized countries anti zones. The presence of the signals from all destinations at a central earth station also allows security agencies the option of monitoring any traffic deemed to be contrary to the national interest.

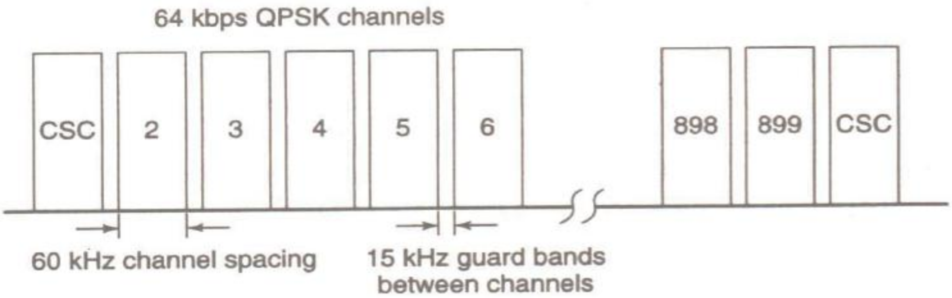


FIGURE Frequency plan for a 54-MHz transponder carrying 900 demand access channels. Each channel has an occupied RF bandwidth of 45 kHz and carries one 64-kbps signal. Channel 1 and channel 900 are common signaling channels (CSC) used by the demand assignment system to set up access to the other 898 channels.

Demand access systems require two different types of channel: a common signalling channel (CSC) and a communication channel. A user wishing to enter the communication network first calls the controlling earth station using the CSC, and the controller then allocates a pair of channels to that user. The CSC is usually operated in random access mode because the demand for use of the CSC is relatively low messages are short, and the CSC is therefore lightly loaded, a requirement for any DA link. Packet transmission techniques are widely used in demand access systems became of the need for addresses to determine the source and destination of signals. Section 6: discusses the design of packets for use in satellite communication systems. Bent pipe transponders are often used in demand access mode, allowing any configuration of FDMA channels to be adopted. There seem to be few standards for demand access systems in the satellite communication industry, with each network using a different proprietary configuration. Figure shows a typical 54 MHz bandwidth Ku bank transponder frequency plan for the inbound channels of a VSAT network using frequents division multiple access with single channel per carrier and demand access (FDMA-SCPC-DA) on the inbound link.

The individual outbound RF channels are 45 kHz wide, to accommodate the occupied bandwidth of 64-kbps bit streams transmitted using QPSK and RRC filters with a = 0.4. A guard band of 15 kHz is allowed between each RF channel. so one RF channel requires a total bandwidth of 60 kHz. A 54 MHz bandwidth transponder can accommodate 900 of these 60 kHz channels, but it is unlikely that all are used at the same time. Many VSAT systems are power limited, preventing the full use of the transponder bandwidth, and the statistics of .demand access systems ensure that tie likelihood of all the channels being used at one time is small. Considerable backoff is required in a bent pipe transponder with large numbers of FDMA channels.

CODE DIVISION MULTIPLE ACCESS (CDMA)

In CDMA satellite systems, each uplink earth station is identified by an address code imposed on its carrier. Each uplink earth station uses the entire bandwidth transmits through the satellite whenever desired. No bandwidth or time sharing is required in CDMA satellite systems. Signal identification is achieved at a receiving earth station by recognising the corresponding address code.

There are three CDMA techniques as follows:

1. Direct sequence CDMA (DS-CDMA)

In this technique, an addressed pseudo-noise (PN) sequence generated by the PN code generator of an uplink earth station together with the information data are modulated directly on the carrier as shown in Fig. 9.28a. The same PN sequence is used synchronously at the receiving earth station to despread the received signal in order to receive the original data information (Fig. 9.28b).

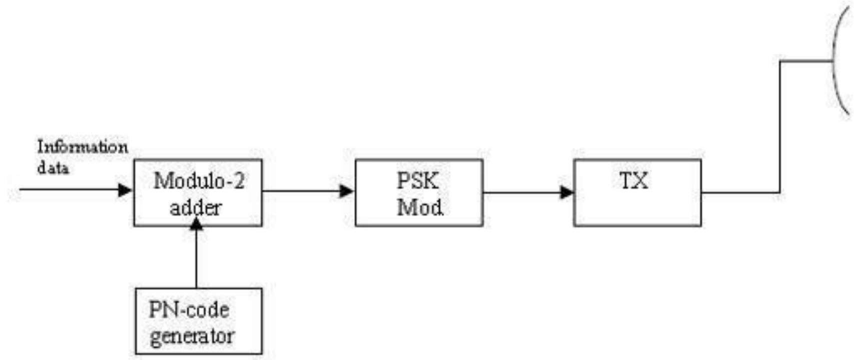
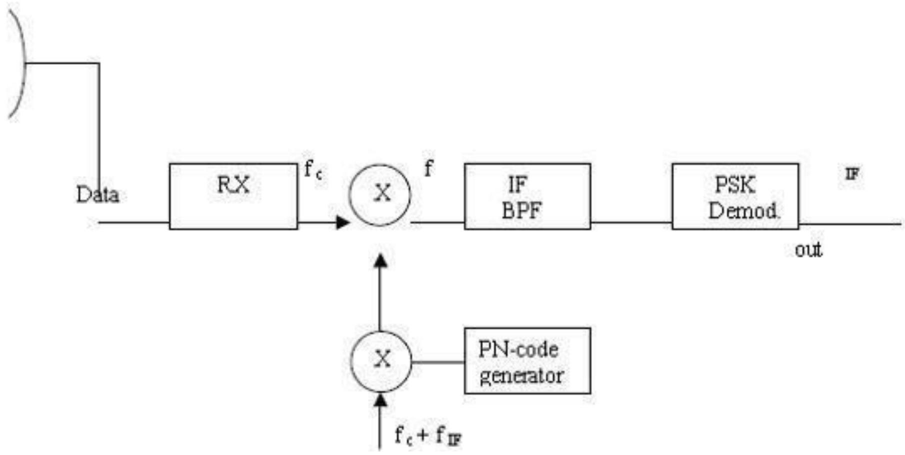


Fig. 9.28a



The bits of the PN sequence are referred to as chips. The ratio between the chip rate and information rate is called the spreading factor. Phase-shift-keying modulation schemes are commonly used for these systems. The most widely used binary PN sequence is the maximum length linear feedback shift register sequence (m-sequence) which is generated by an m-stage shift register. The m-sequence has a period of 2 m - 1. Table 2.3 gives the properties of the sequence sets which exhibit small peak cross-correlation values suitable for DSCDMA.

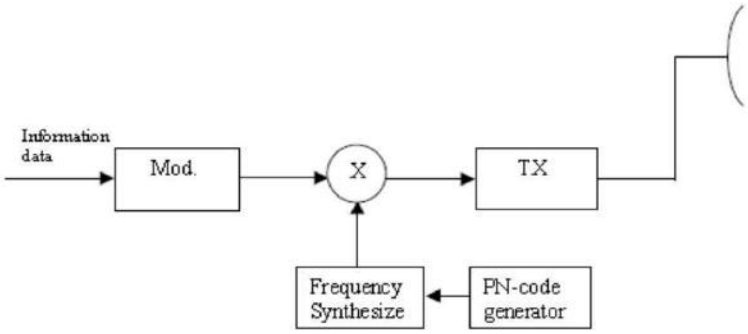
Properties of sequence sets with a period of 2^m-1

Family	m	Set size	$\lvert R_{ur,max} \rvert$
Gold	Odd	$2^m + 1$	$1 + 2^{(m+1)/2}$
Gold	2 (mod 4)	$2^m + 1$	$1 + 2^{(m+2)/2}$
Kasami (small set)	Even	$2^{m/2}$	$1 + 2^{m/2}$
Kasami (large set)	Even	$2^{m/2}(2^m + 1)$	$1 + 2^{(m+2)/2}$
Bent	0 (mod 4)	$2^{m/2}$	$1 + 2^{m/2}$

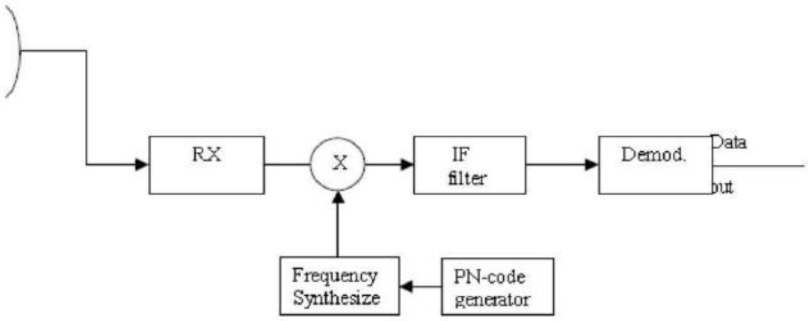
There are two types of DS-CDMA techniques: synchronous and asynchronous. In a synchronous system, the entire system is synchronized in such a way that the PN sequence period (code period) or bit duration of all the uplink carriers in the system are in time alignment at the satellite. This requires that all stations have the same PN sequence period and the same number of chips per PN sequence length. Hence, a synchronous DS-CDMA must have the type of network synchronization used in a TDMA system but in a much simpler form. However, in an asynchronous DS-CDMA satellite no time alignment of the PN sequence period at the satellite is required and each uplink carrier operates independently with no overall network synchronization. Therefore, the system complexity is much simpler than a synchronous system.

2. Frequency hopping CDMA (FH-CDMA)

The block diagram of an FH-CDMA transmitter/receiver is shown in Fig.



Transmitter



Receiver

Here, the addressed PN sequence is used to continually change the frequency of the carrier at the uplink earth station (hopping). At the receiver, the local PN code generator produces a synchronized replica of the transmitted PN code which changes the synthesizer frequency in order to remove the frequency hops on the received signal, leaving the original modulated signal untouched. Non-coherent M-ary FSK modulation schemes are commonly used for these systems.

3. Hybrid CDMA

A hybrid CDMA system employs a combination of DS-CDMA and FHCDMA techniques. In all these techniques, a larger bandwidth is produced than that which will be generate by the modulation alone. Because of this spreading of the signal spectrum, CDMA systems are also referred to as spread spectrum multiple access (SSMA) systems. Spreading the spectrum of the transmitted signal has important applications in military satellite systems since it produces inherent anti jam advantages. In addition to anti jamming protection, another important feature of these systems is their low probability of interception (LPI) and hence, reduces the probability of reception by unauthorized users.

Spread Spectrum Transmission and Reception

This discussion of CDMA for satellite communications will be restricted to direct sequence systems, since that is the only form of spread spectrum that has been used by commercial satellite systems to date. The spreading codes used in DS -SS CDMA systems are designed to have good autocorrelation properties and low cross -correlation. Various codes have been developed specifically for this purpose, such as Gold and Kasarni codes.

The DS -SS codes will all be treated as Pseudonoise (PN) sequences in this discussion. Pseudonoise refers to the spectrum of code, which appears to be a random sequence of bits (or chips) with a flat, noise like spectrum. The generation of .a DS -SS signal is illustrated in Figure 1. We will begin by assuming that the system uses baseband signals Most DS -SS systems generate spread spectrum signals using BPSK modulated versions of the data stream, but it is easier to see how a DS -SS system operates if the signals are first considered at baseband. In Figure 1, a bit stream containing traffic data at a rate Rb, converted to have levels of +1 and —1 V corresponding to the logical states 1 and 0, is multiplied by a PN sequence, also with levels +1 and — 1 V, at a rate M X Rb Chips per second. Each data bit results in the transmission of a complete PN sequence of length M chips.

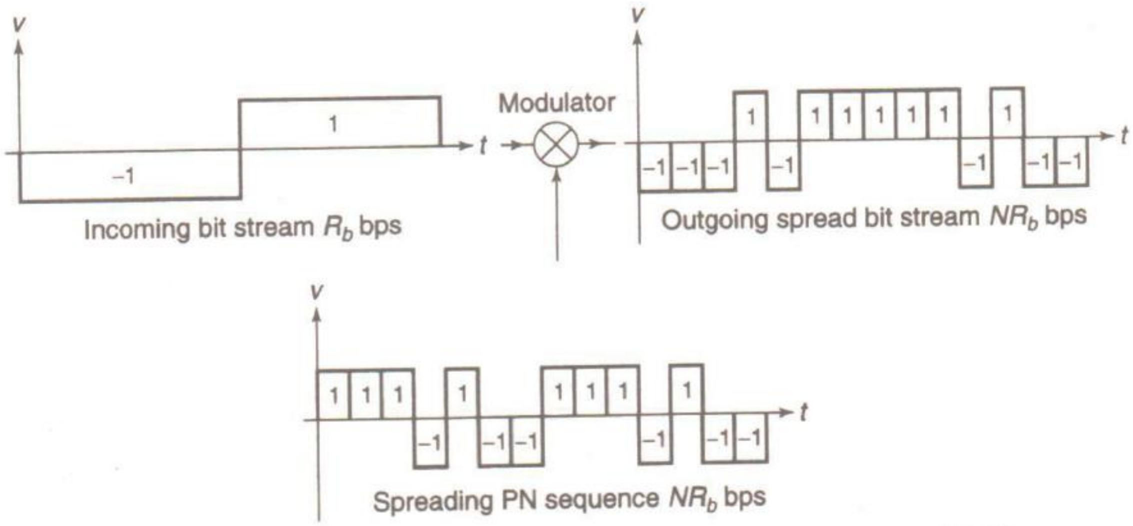


FIGURE 1 The basic principle of a direct sequence spread spectrum (CDMA) system. Each incoming message data bit is multiplied by the same PN sequence. In this example the message sequence is −1 +1 and the PN sequence is +1 +1 +1 −1 +1 −1 −1.

In the example shown in Figure 6.16, the seven chip spreading code sequence is 1110100, which is converted to +1 +1 +1 —1 +1 —1 —1. The spreading sequence multiplies the data sequence 0 1, represented as —1 +1, leading to the transmitted sequence —1 —1 —1 +1 —1 +1 +1 +1 +1 +1 —1+1—1 —1 shown at the right in Figure1.

Recovery of the original data stream of bits from the DS-SS signal is achieved by multiplying the received signal by the same PN code that was used to generate it. The process is illustrated in Figures 2 and 3.

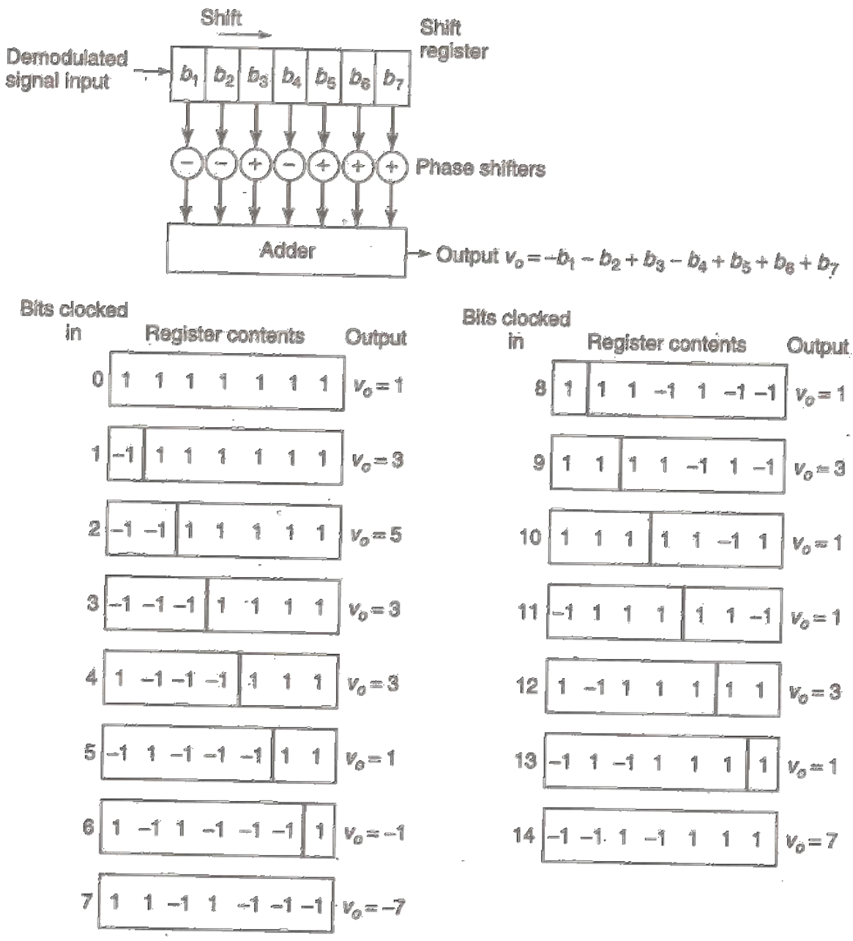


Figure 2: Data bit recovery using an IF correlator (matched filter). In this example the PN sequence is seven bits long for illustration. The CDMA chips from the receiver are clocked into the shift register serially and the shift register contents passed through phase shifters and added. The phase shifters convert —1 chips to +1 when the correct code is in the shift register such that all the voltages add to a maximum when the received sequence is correct. This figure shows the shift register contents and adder output for the chip sequence in Figure 1. Note that a high spurious output of 5 occurs at the third clock step, indicating that the seven bit sequence used here for illustration has poor autocorrelation properties.

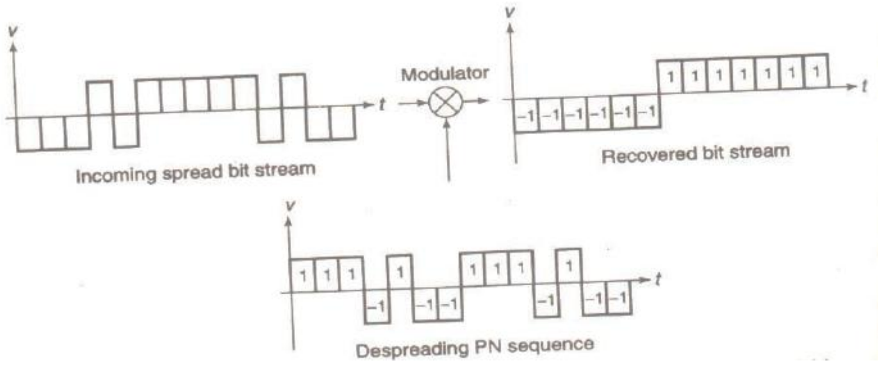


Figure 3: A baseband correlator for dispreading CDMA signals. The original bit stream is recovered by multiplying the received signal by a synchronized copy of the PN sequence that was used in the transmitter.

TEXT BOOKS:

1. Satellite communications-Timothy Pratt, Charles Bostian and Jeremy Allnutt, WSE, Wiley Publications, 2^{nd} Edition,2003.
2. Satellite communications Engineering-Wilbur L.Pritchard, Robert A Nelson and Henri G.Suyderhoud, 2^{nd} Edition, Pearson Publications, 2003.

REFERENCES:

1. Satellite communications - Design Principles-M.Richharia, BS Publications, 2^{nd} Edition, 2003.

UNIT-IV
EARTH STATION TECHNOLOGY

INTRODUCTION

Earth station is a vital element in any satellite communication network. The function of an earth station is to receive information from or transmit information to, the satellite network in the most cost-effective and reliable manner while retaining the desired signal quality. The design of earth station configuration depends upon many factors and its location. But it is fundamentally governed by its location which are listed below,

- In land
- On a ship at sea
- Onboard aircraft

The factors are

- Type of services
- Frequency bands used
- Function of the transmitter
- Function of the receiver
- Antenna characteristics

EARTH STATION CONFIGURATION

Any earth station consists of four major subsystems

- Transmitter
- Receiver
- Antenna
- Tracking equipment

Two other important subsystems are

- Terrestrial interface equipment
- Power supply.

The earth station depends on the following parameters

- Transmitter power
- Choice of frequency
- Gain of antenna
- Antenna efficiency
- Antenna pointing accuracy
- Noise temperature
- Local conditions such as wind, weather etc,
- Polarization
- Propagation losses

The functional elements of a basic digital earth station are shown in the below figure

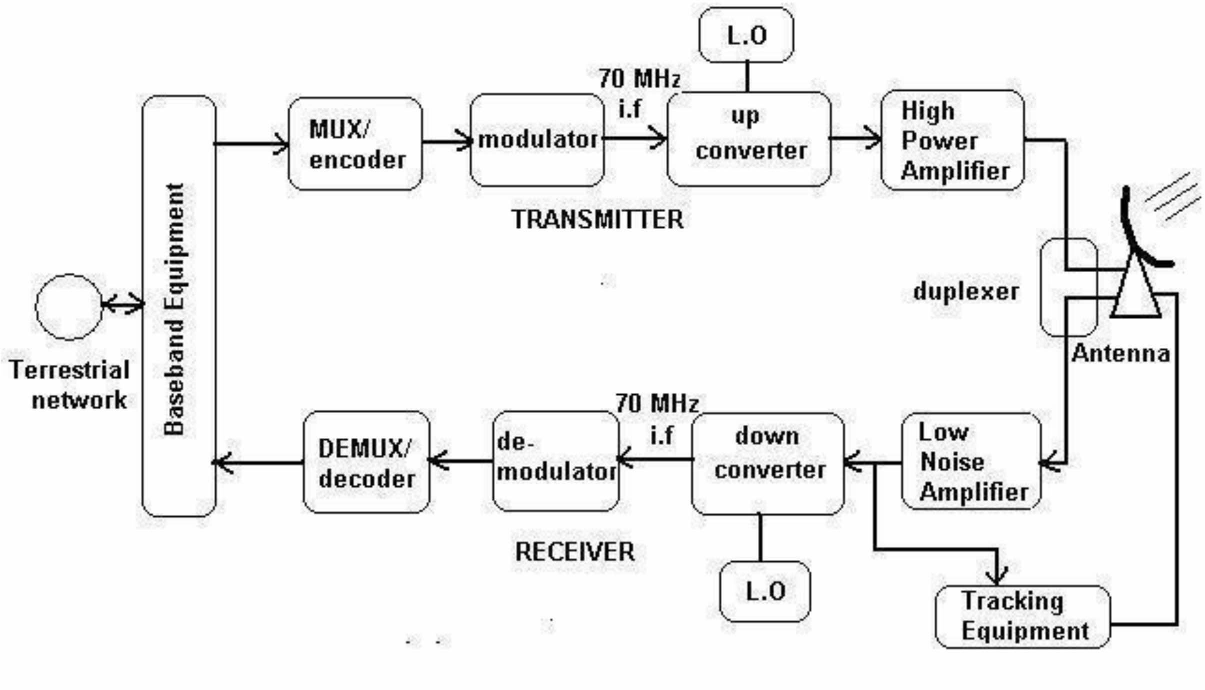


Fig- General Configuration of an Earth Station

- Digital information in the form of binary digits from terrestrial networks enters earth station and is then processed (filtered, multiplexed, formatted etc.) by the base band equipment.

- The encoder performs error correction coding to reduce the error rate, by introducing extra digits into digital stream generated by the base band equipment. The extra digits carry information. The presence of noise and non-ideal nature of any communication channel produces error rate is established above which the received information is not stable.
- The function of the modulator is to accept the symbol stream from the encoder and use it to modulate an intermediate frequency (I.F) carrier. In satellite communication, I.F carrier frequency is chosen at 70 MHz for communication using a 36 MHz transponder bandwidth and at 140 MHz for a transponder bandwidth of 54 or 72 MHz. The I.F is needed because it is difficult to design a modulator that works at the uplink frequency of 6 GHz (or 14GHz) directly.
- The modulated I.F carrier is fed to the up-converter and frequency-translated to the uplink r-f frequency.
- This modulated R.F carrier is then amplified by the high power amplifier (HPA) to a suitable level for transmission and radiation by the antenna to the satellite.
- On the receive side, the earth station antenna receives the low-level modulated R.F carrier in the downlink frequency spectrum.

- The low noise amplifier (LNA) is used to amplify the weak received signals and improve the signal to Noise ratio (SNR). The error rate requirements can be met more easily.
- R.F is to be reconverted to I.F at 70 or 140 MHz because it is easier design a demodulation to work at these frequencies than 4 or 12 GHz.
- The demodulator estimate which of the possible symbols was transmitted based on observation of the received if carrier.
- The decoder performs a function opposite that of the encoder. Because the sequence of symbols recovered by the demodulator may contain errors, the decoder must use the uniqueness of the redundant digits introduced by the encoder to correct the errors and recover information-bearing digits.
- The information stream is fed to the base-band equipment for processing for delivery to the terrestrial network.
- The tracking equipments track the satellite and align the beam towards it to facilitate communication.

ANTENNA SUBSYSTEM

The antenna system consist of

- Feed System
- Antenna Reflector
- Mount
- Antenna tracking System

FEED SYSTEM

The feed along with the reflector is the radiating/receiving element of electromagnetic waves. The reciprocity property of the feed element makes the earth station antenna system suitable for transmission and reception of electromagnetic waves. The way the waves coming in and going out is called feed configuration Earth Station feed systems most commonly used in satellite communication are:

i)Axi-Symmetric Configuration

ii)Asymmetric Configuration

i)Axi-Symmetric Configuration

In an axi-symmetric configuration the antenna axes are symmetrical with respect to the reflector, which results in a relatively simple mechanical structure and antenna mount.

- **Primary Feed**

In primary, feed is located at the focal point of the parabolic reflector. Many dishes use only a single bounce, with incoming waves reflecting off the dish surface to the focus in front of the dish, where the antenna is located. When the dish is used to transmit, the transmitting antenna at the focus beams waves toward the dish, bouncing them off to space. This is the simplest arrangement.

- **Cassegrain**

Many dishes have the waves make more than one bounce .This is generally called as folded systems. The advantage is that the whole dish and feed system is more compact. There are several folded configurations, but all have at least one secondary reflector also called a sub reflector, located out in front of the dish to redirect the waves.

A common dual reflector antenna called Cassegrain has a convex or hyperboloid sub reflector positioned in front of the main dish, closer to the dish than the focus. This sub reflector bounces back the waves back toward a feed located on the main dish's center, sometimes behind a hole at the center of the main dish. Sometimes there are even more sub reflectors behind the dish to direct the waves to the fed for convenience or compactness.

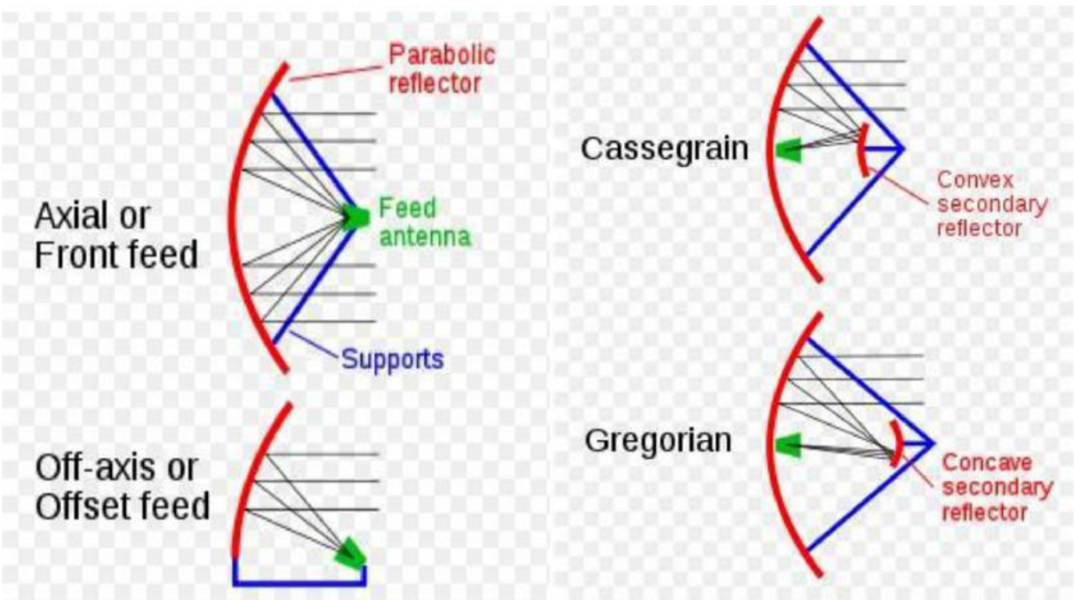
- **Gregorian**

This system has a concave secondary reflector or ellipsoid sub reflector located just beyond the primary focus. This also bounces the waves back toward the dish.

ii)Asymmetric Configuration

- **Offset or Off-axis feed**

The performance of tan axi-symmetric configuration is affected by the blockage of the aperture by the feed and the sub reflector assembly. The result is a reduction in the antenna efficiency and an increase in the side lobe levels. The asymmetric configuration can remove this limitation. This is achieved by off-setting the mounting arrangement of the feed so that it does not obstruct the main beam. As a result, the efficiency and side lobe level performance are improved.



ANTENNA REFLECTOR

Mostly parabolic reflectors are used as the main antenna for the earth stations because of the high gain available from the reflector and the ability of focusing a parallel beam into a point at the focus where the feed, i.e., the receiving/radiating element is located .For large antenna system more than one reflector surfaces may be used in as in the cassegrain antenna system.

Earth stations are also classified on the basis of services for example:
1.Two way TV ,Telephony and data
2. Two way TV
3.TV receive only and two way telephony and data
4.Two way data

From the classifications it is obvious that the technology of earth station will vary considerably on the performance and the service requirements of earth station.
For mechanical design of parabolic reflector the following parameters are required to be considered:

- Size of the reflector
- Focal Length /diameter ratio
- RMS error of main and sub reflector
- Pointing and tracking accuracies
- Speed and acceleration
- Type of mount
- Coverage Requirement
- Wind Speed

The size of the reflector depends on transmit and receive gain requirement and beamwidth of the antenna. Gain is directly proportional to the antenna diameter whereas the beamwidth is inversely proportional to the antenna diameter .for high inclination angle of the satellite, the tracking of the earth station becomes necessary when the beamwidth is too narrow.
The gain of the antenna is given by

$$\text{Gain}= (\eta 4\Pi A_{eff})/ \lambda^2$$

Where A_{eff} is the aperture
λ is wave length
η is efficiency of antenna system
For a parabolic antenna with circular aperture diameter D, the gain of the antenna is :

$$\text{Gain}= (\eta 4\Pi/ \lambda^2)(\Pi D^2/4)$$

$$= \eta\ (\Pi D/ \lambda)^2$$

The overall efficiency of the antenna is the net product of various factors such as

1. Cross Polarization
2. Spill over
3. Diffraction
4. Blockage
5. Surface accuracy
6. Phase error
7. Illumination

In the design of feed ,the ratio of focal length F to the diameter of the reflector D of the antenna system control the maximum angle subtended by the reflector surface on the focal point. Larger the F/D ratio larger is the aperture illumination efficiency and lower the cross polarization

ANTENNA MOUNT

Type of antenna mount is determined mainly by the coverage requirement and tracking requirements of the antenna systems. Different types of mounts used for earth station antenna are:

i)The Azimuth –elevation mount

This mount consists of a primary vertical axis. Rotation around this axis controls the azimuth angle. The horizontal axis is mounted over the primary axis, providing the elevation angle control.

ii)The X-Y mount.

It consists of a horizontal primary axis(X-axis) and a secondary axis (Y-axis) and at right angles to it.Movement around these axes provides necessary steering.

INPUT BACK-OFF

In order to reduce the intermodulation distortion, the operating point of the TWT must be shifted closer to the linear portion of the curve, the reduction in input power being referred to as input backoff . The input backoff is the difference in decibels between the carrier input at the operating point and the saturation input which would be required for single-carrier operation.

HIGH POWER AMPLIFIER

Amplifier may work with signals of all level, depending on where they are in the signal chain. One type of Amplifier takes low power signals and increases them greatly in order to send the signal over a wire or from a dish. This is often called as high power amplifier, typical hardware used for earth station HPAs is similar to that used aboard the satellite for the transponders, but they typically operate at much higher powers.

Two most commonly used high power amplifier are TWT and klystron. TWT amplifier can offer bandwidths of the order of 500Mhz and are capable of providing powers of up to 10kW.

Klystrons are narrowband devices typically offering bandwidths of the order 40Mhz ,tunable over the entire 500 Mhz bandwidth. Maximum power rate of the order of 3kW.

The configuration of high power amplifiers depends on the type of application. For multi-carrier operation; two types of configuration are used depending on the stage where the carrier are combined. in a single amplifier configuration all the carriers are combined before the amplifier and therefore only one HPA is used as shown in the below figure.

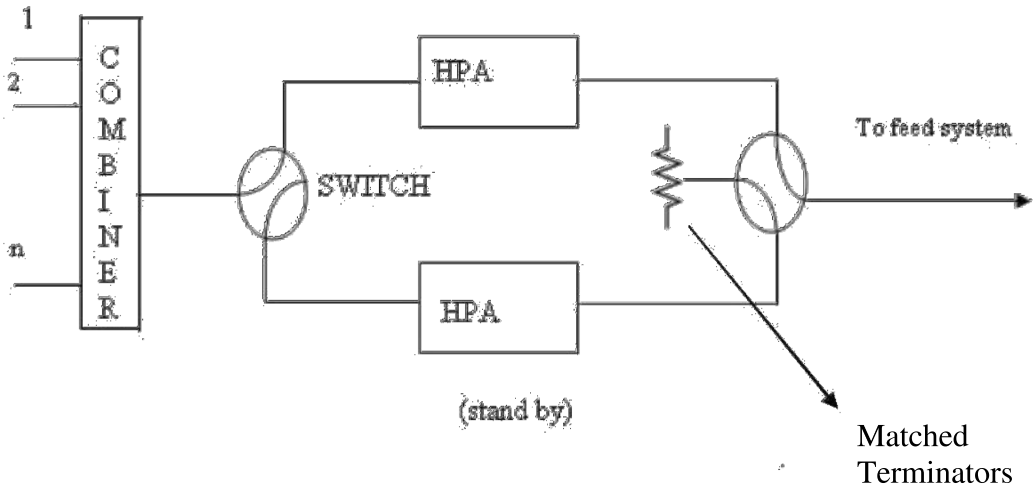


Fig-single stage HPA

In a multiple amplifier configuration each HPA amplifies one or a few of the total carriers. All the amplified signals are then combined at the output of the HPAs as shown in below figure.

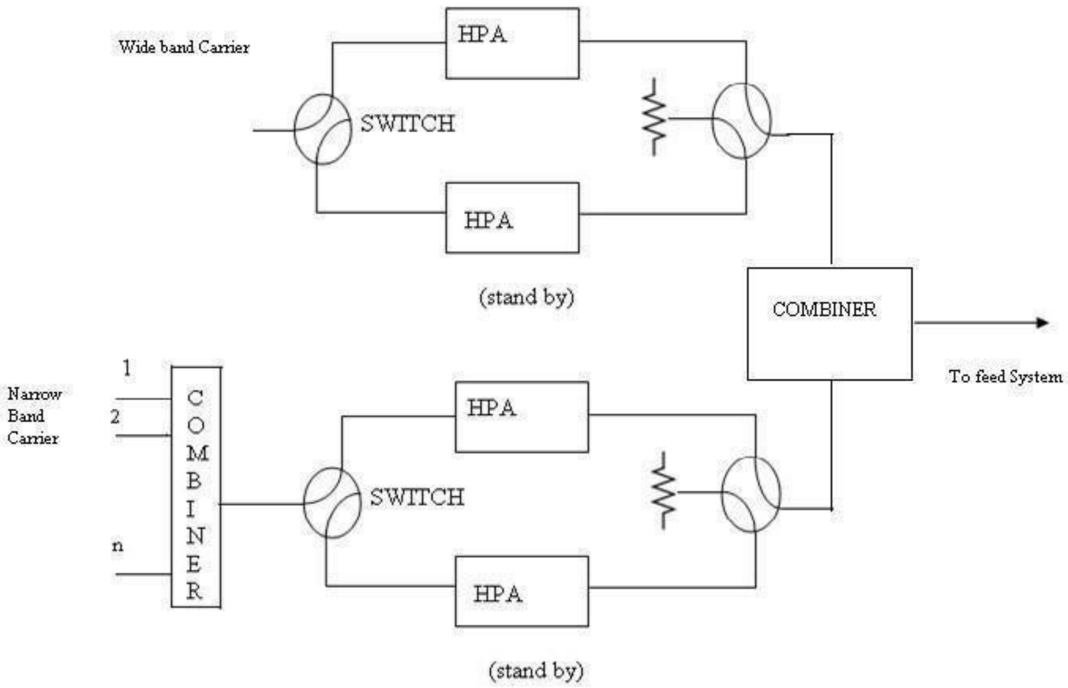


Fig-multi stage HPA

The high power amplifier (HPA) in an earth station facility provides the RF carrier power to the input terminals of the antenna that, when combined with the antenna gain, yields the equivalent isotropic radiated power (EIRP) required for the uplink to the satellite. The

Waveguide loss between the HPA and the antenna must be accounted for in the calculation of the EIRP.

An earth station HPA can be one of three types: a klystron power amplifier (KPA), a traveling wave tube amplifier (TWTA), or a solid state power amplifier (SSPA). The KPA and TWTA achieve amplification by modulating the flow of electrons through a vacuum tube. Solid state power amplifiers use gallium arsenide (GaAs) field effect transistors (FETs) that are configured using power combining techniques. The klystron is a narrowband, high power device, while TWTAs and SSPAs have wide bandwidths and operate over a range of low, medium, and high powers.

The principal technical parameters characterizing an amplifier are its frequency, and width, output power, gain, linearity, efficiency, and reliability. Size, weight, cabinet design, ease of maintenance, and safety are additional considerations. Cost factors include the cost of installation and the long term cost of ownership.

LOW NOISE AMPLIFIER

The low-noise amplifier (LNA) adds little noise to the carrier being amplified, and at the same time it provides sufficient amplification for the carrier to override the higher noise level present in the following mixer stage. In calculations involving noise, it is usually more convenient to refer all noise levels to the LNA input, where the total receiver noise may be expressed in terms of an equivalent noise temperature.

In a well-designed receiver, the equivalent noise temperature referred to the LNA input is basically that of the LNA alone. The overall noise temperature must take into account the noise added from the antenna. The equivalent noise temperature of a satellite receiver may be on the order of a few hundred kelvins.

Types of LNA in common use today include:

- Uncooled Field-Effect Transistor (FET) amplifiers which have a noise temperature of 55 to 75K at 4 GHz or around 200K at 11 GHz
- Amplifiers cooled by thermoelectric diodes which have a noise temperature of 35K to 45K at 4 GHz and around 120K at 11 GHz

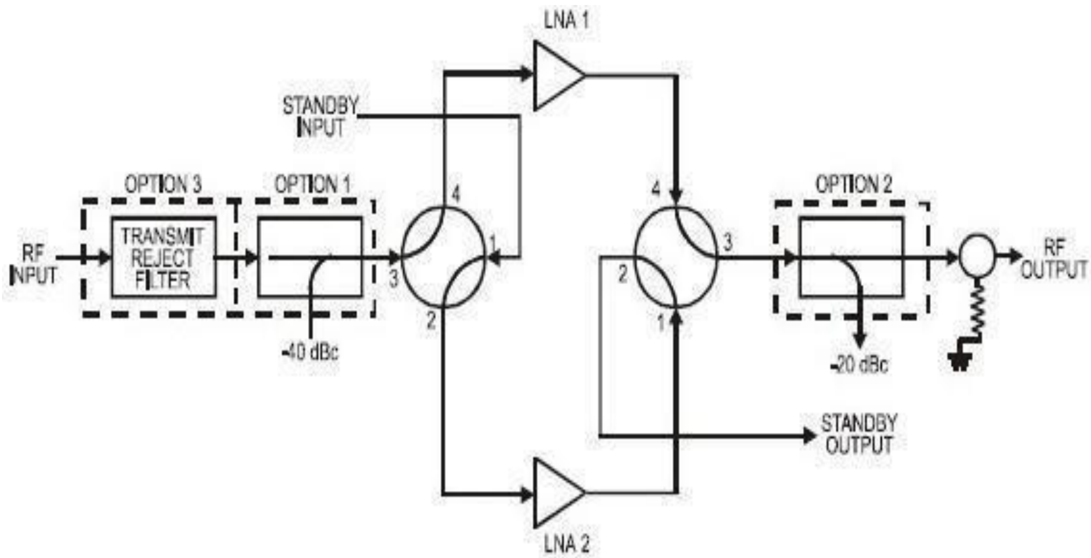


Fig-multi stage LNA

There are two variations of LNA they are :

A low noise block-downconverter (or LNB) is the receiving device of a parabolic satellite dish antenna of the type commonly used for satellite TV reception. The device is sometimes called an LNA (for low noise amplifier), LNC (for low noise converter) or even LND (for low noise downconverter) but as block-downconversion is the principal function of the device, LNB is the preferred term, although this acronym is often incorrectly expanded to the incomplete descript ions, low noise block or low noise block converter.

It is functionally equivalent to the dipole antenna used for most terrestrial TV reception, although it is actually waveguide based. Inside the LNB waveguide a metal pin, or probe, protrudes into the waveguide at right angles to the axis and this acts as an aerial, collecting the signal travelling down the waveguide.

The LNB is usually fixed on the satellite dish framework, at the focus of the reflector, and it derives its power from the connected receiver. This power is sent "up" the same cable that carries the received signals "down" to the receiver. The corresponding component in the transmit link uplink to a satellite is called a Block upconverter (BUC).

EARTH STATION TRACKING SYSTEM

Tracking is essential when the satellite drift, as seen by an earth station antenna is a significant fraction of an earth station's antenna beam width. An earth station's tracking system is required to perform some of the functions such as

i) Satellite acquisition ii)Automatic tracking iii)Manual tracking iv)Program tracking.

a)Satellite Acquisition

Before communication can be established it is necessary to acquire a satellite. One method is to program the antenna to perform a scan around the predicted position of the satellite. The automatic tacking is switched on when the receiver signal strength is sufficient to lock the tracking receiver to the beacon.

b)Automatic Tracking:

After acquisition a satellite needs to be tracked continuously. This function is performed by the automatic tracking system .Auto-tack systems are closed-loop control systems and are therefore highly accurate. This tracking mode is the preferred configuration when accuracy is the dominant criterion.

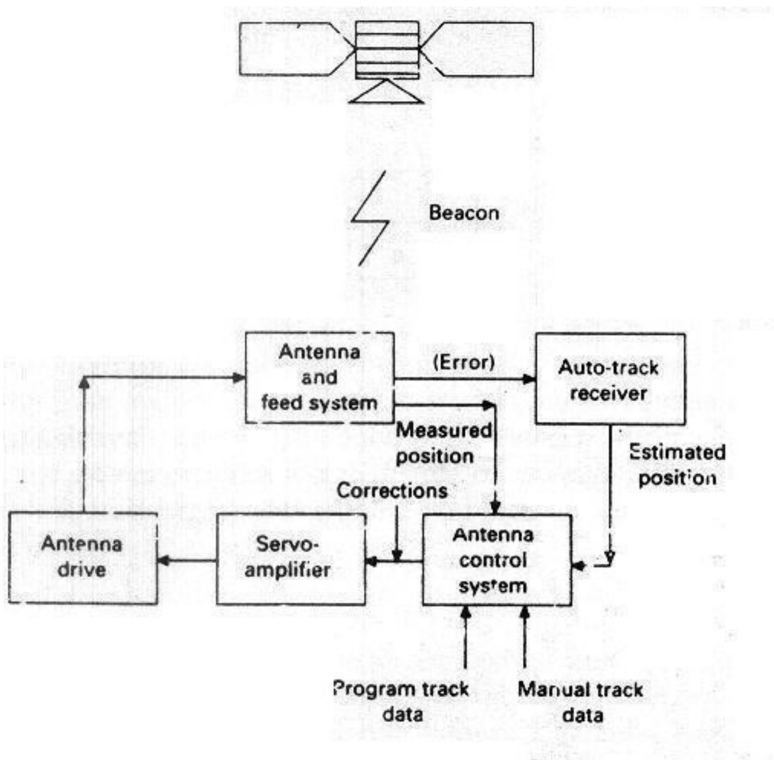
c)Manual track:

To avoid a total loss of communication due to a failure in the tracking system, earth stations generally also have manual mode. In this mode an antenna is moved through manual commands.

d)Program Track:

In this tracking mode the antenna is driven to the predicted satellite position by a computer. The satellite position predictions are usually supplied by the satellite operators. It may be noted that since a program track system is an open-loop control system, its accuracy is mainly governed by the accuracy of the prediction data.

MAIN ELEMENTS OF A SATELLITE TRACKING SYSTEM



Communication satellites transmit a beacon which is used by earth stations for tracking. The received beacon signal is fed into the auto-track receiver where tracking corrections or, in some auto-track systems estimated positions of the satellite are derived. In other auto-track techniques the feed system provides the required components of error signals. The outputs of the auto-track receivers are processed and used to drive each axis of the antenna to the estimated satellite position.

In the manual mode, an operator sets the desired angles for each axis on a control console. This position is compared with the actual antenna position, obtained through shaft encoders, and the difference signal is used to drive the antenna.

In the program track mode the desired antenna position is obtained from a computer. The difference in the desired antenna positions constitutes the error and is used to drive the antenna.

Auto Track system:

There are three main types of auto-track system which have been commonly used for satellite tracking;

i)conical scan; ii)monopulse ; iii)step-track.

i)CONICAL SCAN

The conical scan technique has evolved from the lobing technique used in the RADARS (Radio detection and ranging).In this technique an antenna beam is switched between two positions. When an approaching target is at the centre of these beams the echoes from each beam are equal in magnitude, but at other positions unequal. The antenna position is adjusted such that the amplitudes of echoes are equalized.

This concept was extended to a continuous rotation of a beam around a target ,giving rise to the conical scan technique .

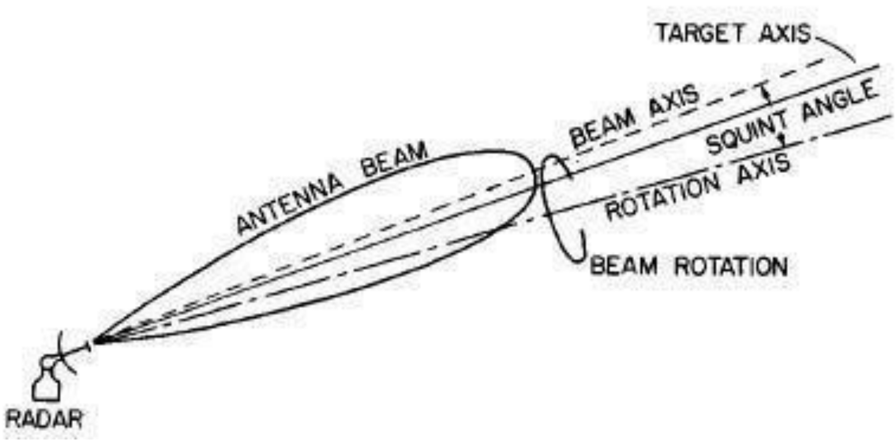


Figure shows the principle of this technique .An antenna beam is rotated around an axis (rotation axis) which is offset from the beam axis by a small squint angle .Whenever the satellite is off the target axis, the envelope of the received beacon is modulated at the rate of beam rotation.

The tracking receiver in the conical scan technique uses the full received power for extracting errors and hence the sensitivity requirement of the auto track receiver is reduced .The accuracy of the system is affected by amplitude disturbances .moreover the maximum gain of the antenna is not realized because of the squint introduced into the main beam. As a result of these limitations conical systems are surpassed by other tracking techniques.

ii)MONOPULSE TECHNIQUE

In the mono pulse technique the errors for driving the antenna system are derived by simultaneous lobbing of the received beacon –hence the name Static-split or monopulse. The inherent susceptibility of the conical scan technique to amplitude fluctuations is eliminated since errors are derived from simultaneous measurements.

Several mono pulse schemes such as amplitude comparison, phase comparison or amplitude phase comparison are possible. The amplitude comparison technique is the simplest and commonly used for satellite tracking. The basic principle of its operation is understood from Figure

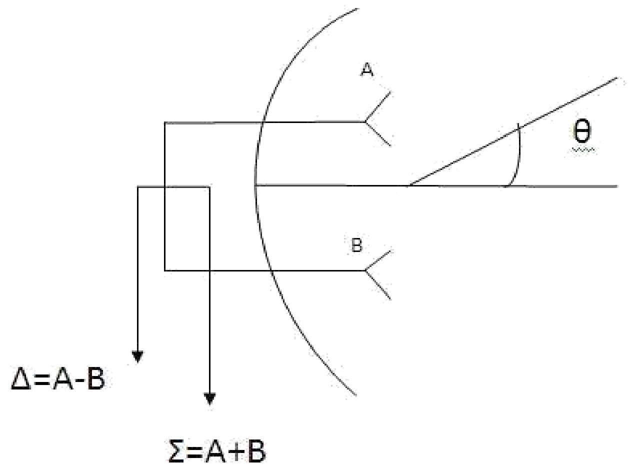


Fig: Mono pulse

Two horns are offset and mounted in a plane. Two types of patterns can be distinguished-a sum pattern Σ and a difference pattern . The difference pattern output with respect to sum pattern is zero when the satellite is centered, otherwise the output is proportional to the tracking error. It should be emphasized that the difference pattern must be detected with respect to the sum pattern to obtain the error. This can be achieved by a coherent detection process .That the difference pattern changes phase stability of the receiver be good.

Several techniques can be used to determine the sum and difference signals. One commonly used technique is used to use microwave circuits known as hybrids. Referring to fig1 a power from two horns A and B is fed into a microwave hybrid. A hybrid consists of two input arms ,A and B and two output arms the sum arm and the difference arm .The property of the hybrid is that the input powers appear as a sum in the 'Sum' arm and as a difference in the 'difference' arm.

iii) STEP –TRACK SYSTEM

In the step –track technique, error signals are derived from amplitude sensing. The operation is based on maximization of the received signal by moving the axes in small steps (hence the name step track) until a maximization is affected. The tracking accuracy of the technique depends on the step size and the signal to noise ratio. For high signal to noise ratios the standard deviation of tracking error approaches the step size.

Recent Tracking Techniques:

There have been some interesting recent developments in auto-track techniques which can potentially provide high accuracies at a low cost .In one proposed technique the sequential lobing technique has been I implemented by using rapid electronic switching of a s single beam which effectively approximates simultaneous lobing. The high rate of switching is achieved by the use of an electronically controlled feed. This technique, sometimes referred to as electronic beam squinting, requires a simple single channel receiver and has been reported to achieve a tracking accuracy approaching that of the auto-track technique.

TERRESTRIAL INTERFACE:

The terrestrial interface comprises a wide variety of equipment. At one extreme, when the terminal is a mobile or receive -only station, there may be no terrestrial interface equipment at all. The operating devices, such as TV receivers, telephones, data sets, and so on, are used right at the earth station. At the other extreme, we find the interface equipment necessary in a large commercial satellite system for fixed service. In such cases, hundreds of telephone channels, together with data and video, are brought to the station by microwave and cable systems using either frequency- or time -division terrestrial multiplex methods. The signals must be changed from those formats into formats suitable for satellite transmission. In an easy case, frequency –division multiplex groups and supergroups, as brought in from terrestrial transmission facilities, can be transmitted directly or with simple translation in baseband frequency from the satellite after modulation and up -conversion, but in many cases it is necessary to reformat extensively for terrestrial circuits. Individual telephone channels, for instance, May all be transmitted on the same carrier, which is received by many earth stations in the network. The return channels for particular conversation circuits will be coming in on various carrier frequencies, depending on their source, and they must be tagged and put together with the corresponding outgoing circuit to make up a terrestrial circuit. This can be a complex process. The presence of video and data complicates matters further.

If the satellite transmission is single channel per carrier, it is necessary to bring each terrestrial carrier down to baseband before remodulation. The interfaces between terrestrial time –division and satellite frequency –division systems, and vice versa, are complicated and can be accomplished in a variety of ways. Television video signals must often be separated from order wire channels, program sound channels, cueing channels, and so on, and then matched up again at the proper point.

Usually, in the systems engineering and programming planning phase it is only necessary to be alert to the problems and possibilities, the detailed design can be saved until later in the program.

PRIMARY POWER

Primary power systems vary from plain battery- or solar -cell -operated remote transmitters for data gathering to huge, combined commercial power and diesel generator systems for large stations. Most transmit and receive earth stations require some kind of "no -break" power system, that is emergency power to continue the communications during commercial power outages.

Such power outages are frequent, even in highly organized industrial areas, if for no reason other than thunderstorms. The no –break transition derives its name from the necessity to make the change over from one power system to another without any interruption in service. Almost all systems today use batteries to effect this transition. Some systems have been devised in which motor generators store enough energy in flywheels to permit a smooth mechanical transition.

TEST METHODS

Noise Power Ratio (NPR)

Earth stations are typically provided with complex test equipment, ranging from that necessary for routine measurements of voltage, power, temperature, and soon, to sophisticated and specialized measurements unique to satellite communication. One of these is noise power ratio (NPR), the traditional measure of intermodulation noise for FDM systems in the communications field. The principle of NPR measurement involves loading the entire baseband spectrum, save for the one voice -frequency channel slot, with noise, simulating in total the loading of the system by actual voice traffic in all but that channel. Noise appearing in the unloaded slot is a manifestation of intermodulation. The ratio of that noise power to the per -channel loading noise power is the NPR. NPR is measured by a setup as shown in Figure. The system can be between any two points of interest. The noise generator band is limited by filters to the baseband, and the noise generator level is set to simulate full load according to the CCIR formulas

$$P = -15 + 10 \log N \text{ dBmO}, \qquad N \geq 240$$

$$P = -1 + 4 \log N \text{ dBmO}, \qquad N < 240$$

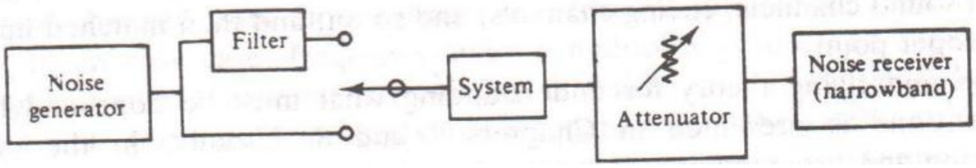


Figure Noise power ratio test setup.

The Measurement of G/T

System temperature Ts can be determined by conventional laboratory noise generator measurement of receiver noise figure and radiometric measurements of antenna temperature. The basic system parameter G/T s also requires a knowledge of antenna gain, and as the antennas get larger, this characteristic is not so easy to get. The gain of smaller antennas, say less than 7 or 8 m, can be found from pattern measurements on a range or by comparison to a gain standard, but these methods are cumbersome and may be impractical for larger antennas. Large earth stations, with antenna sizes up from 10 m, can sometimes use a carefully calibrated satellite signal to measure G/Ts.

SATELLITE NAVIGATION & THE GLOBAL POSITIONING SYSTEM

INTRODUCTION

The Global Positioning Satellite System (GPS) has revolutionized navigation and position location. It is now the primary means of navigation for most ships and aircraft and is widely used in surveying and many other applications. The GPS system, originally called NAVSTAR, was developed as a military navigation system for guiding missiles, ships. And aircraft to their targets. GPS satellites transmit L -band signals that are modulated by several codes. The C/A (coarse acquisition) code was made available to the public in the mid -1980s. The secure high accuracy P code allows authorized users (mainly military) to achieve positioning accuracy of 3m. This was the accuracy that the military users wanted for targeting smart bombs and cruise missiles, but such accuracies are also useful for auto -landing aircraft in fog and for docking ships in bad weather.

The GPS system has been successful because it provides a direct readout of the present position of a GPS receiver with a typical accuracy of 30 m. There are other position location systems, such as LORAN, (a contraction of long range navigation) that can also provide direct readout of position, but not with the accuracy and reliability of GPS. The success of GPS is an excellent example of what satellites do best: broadcasting.

An unlimited number of GPS receivers can operate simultaneously because all that a GPS receiver has to do to locate itself is to receive signals from four GPS satellites. The GPS space segment consists of 24 satellites in medium earth orbit (MEO) at a nominal altitude of 20,200 km with an orbital inclination of 55°. The satellites are clustered in groups of four, called constellations, with each constellation separated by 60° in longitude. The orbital period is approximately one-half a sidereal day (11 h 58 min) so the same satellites appear in the same position in the sky twice each day. The satellites carry station -keeping fuel and are maintained in the required orbits by occasional station- keeping maneuvers, just like GEO satellites. The orbits of the 24 GPS satellites ensure that at anytime, anywhere in the world, a GPS receiver can pick up signals from at least four satellites. Up to 10 satellites may be visible at some times, and more than four satellites are visible nearly all of the time. Replacement satellites are launched as needed, so there may be more than 24 operational GPS satellites at any given time.

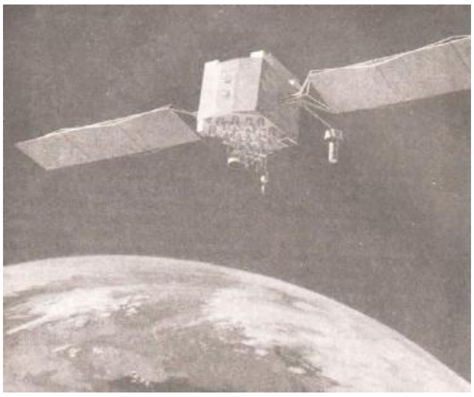


Figure 1: GPS block II-F satellite

Figure.1 shows a GPS satellite. The satellites weigh 1877 kg at launch and have a design lifetime of 10 years. In 2000, there were 30 GPS satellites in orbit, some of which it were spares. Because GPS is an integral part of the defence of the United States, spare GPS satellites are kept in orbit and more spares are ready for immediate launch. The GPS system is operated by the U.S. Air Force from the GPS master control station (MCS) at Falcon Air Force Base in Colorado Springs, Colorado. The MCS and a series of subsidiary control stations around the globe continuously monitor all GPS satellites as they come into view and determine the orbit of each satellite. The MCS and other stations calculate ephemeris data for each satellite, atomic clock error, and numerous other parameters needed for the navigation message.

The data are then transmitted to the satellite using a secure S -band link and used to update onboard data. There are five GPS monitor stations located in Hawaii, Colorado Springs, Ascension Island in the Atlantic Ocean, Diego Garcia in the Indian Ocean and Kwajalein in the Pacific Ocean'. The monitor stations have precise cesium time standards and make continuous measurements of range to all visible satellites. These measurements are performed every 1.5 s, and used to provide updates for the navigation messages.

The position of a GPS receiver is found by trilateration, which is one of the simplest and most accurate methods of locating an unknown position. In trilateration, the distance of the unknown point from three known points is measured. The intersection of the arcs corresponding to three distances defines the unknown point relative to the known points, since three measurements can be used to solve three equations to give the latitude, longitude, and elevation of the receiver. The distance between a transmitter and a receiver can be found by measuring the time it takes for a pulse of RF energy to travel between the two. The distance is calculated using the velocity of electromagnetic waves in free space, which is assumed to be equal the velocity of light, c, with c = 299,792,458 m/s. Time can be measured electronically more accurately than any other parameter by the use of atomic clocks, and this is how the GPS position location system can achieve a measurement accuracy of 1 m in a distance of 20,000 km. To achieve a position location accuracy of 1 m, timing measurements must have an accuracy better than 3 ns. This is possible with modern digital circuitry and a great deal of averaging.

Each satellite carries several high accuracy atomic clocks and radiates a sequence of bits that starts at a precisely known time. A GPS receiver contains a clock that is synchronized in turn to the clock on each satellite that it is receiving. The receiver measures the time delay of the arrival of the bit sequence, which is proportional to the distance between the satellite and the GPS receiver. When the distance of a GPS receiver from three satellites has been measured, the remaining piece of information that is required is the position of each satellite. This is calculated in the GPS receiver using the ephemeris for the satellite orbits that are broadcast by each satellite in its navigation message. Since the time at which the transmitted bit sequence started is known at the receiver, the position of the satellite at that time can be calculated from its orbital data. Making the calculation for four satellites provides the receiver with sufficient information to determine its position with very good accuracy. Four satellites, rather than three, are needed because the clock in the receiver is not inherently accurate enough. The fourth distance measurement provides information from which clock errors in the receiver can be corrected and the receiver clock synchronized to GPS time with an accuracy better than 100 ns.

GPS satellites transmit two signals at different frequencies, known as L1 and L2. The L2 signal is modulated with a 10.23 Mbps pseudorandom (PN) bit sequence called the P code that is used by military positioning systems. The P code is transmitted in an encrypted form known as the Y code, which restricts the use of the P code to authorized users.

The L1 frequency carrier is modulated by a 1.023 Mbps PN sequence called the C/A code that is available for public use, and also carries the P code as a quadrature modulation. The higher bit rate of the P code provides better measurement accuracy than the 1.023 Mbps C/A code. C/A stands for coarse acquisition and P stands for precise.

GPS systems using the secure Y code require the C/A code as an intermediate step in making distance measurements with high accuracy. The accuracy of C/A code receivers was deliberately degraded some of the time by a process called selective availability(SA). SA causes variations in the C/A code satellite transmissions that result in less accurate calculation of position. SA was discontinued in May 2000, but can be reinstituted if the President of the United States declares a National Emergency. The GPS system provides two categories of service. The precise positioning service (PPS) receivers track both P code and C/A code on L1 and L2 frequencies. The PPS is used mainly by military users, since the P code is encrypted into the Y code before transmission and requires decryption equipment in the receiver. Standard positioning service (S PS) receivers track the C/A code on L1. This is the service that is used by the general public. The P(Y) and C/A codes transmitted by each satellite create direct sequence spread spectrum signals which occupy the same frequency bands. Both the C/A codes and the P codes are publicly available, but the P code cannot be recovered in a GPS receiver without a knowledge of the Y code decryption algorithm. In this discussion we will concentrate on the C/A code and its use in position location.

The former USSR built and operated a global navigation system that is very similar to GPS, known in the West as Glonass for global navigation satellite system. Almost everything about Glonass is similar to GPS except the multiple access technique. Glonass uses FDMA, with a different transmit frequency at each satellite. The equivalents of the P code and C/A code can be transmitted by Glonass satellites in RF bandwidths of 20 kHz and 2 kHz, so 100 satellites can be accommodated in a bandwidth of 2 MHz. An FDMA receiver with 100 channels is simpler than a CDMA receiver. A frequency synthesizer that can be tuned to the unique frequency of each satellite is required, rather than the digital correlators that recover the GPS signals in a CDMA receiver.

The European Union is considering building a similar satellite navigation system called Galileo, scheduled for operation by 2008, to provide precise navigation signals without dependence on the United States.

RADIO AND SATELLITE NAVIGATION

Prior to the development of radio, navigation was by compass and landmarks on land, and by the sun and stars at sea. Neither technique provides high accuracy, and shipwrecks mused by inaccurate navigation and foggy weather were a common occurrence. On land, people often got lost in wilderness areas (and still do). Pilots of light aircraft, relying solely on a map and landmarks, would get lost and run out of fuel before they found some- where to land. With a GPS receiver and a map, it is impossible to get lost. GPS receivers we very popular with airplane pilots, owners of sea -going boats, and wilderness hikers. The development of aircraft that could fly above the clouds, and particularly the building of large numbers of bomber aircraft in the 1930s, made radio navigation essential Military thinking after WWI, and during WWII, placed high reliance on the ability bomber aircraft to win a war by destroying the weapon manufacturing capability of the my. During WWII, the allies sent 1000 bomber aircraft at a time to targets in Germany, causing immense destruction to many cities. The philosophy of mass destruction continued after WWII with the development of nuclear bombs, intercontinental ballistic missiles (ICBMs), and cruise missiles. However, bomber aircraft, ICBMs, and cruise missiles must their targets, so accurate navigation is an essential part of each of these weapon sys- This demand for accurate targeting of airborne weapons led to the development of However, the majority of GPS users are now civilian, and the worldwide market for equipment is projected to be worth $25 B by 2005.

Commercial aircraft fly on federal airways using VOR (VHF omni range) beacons. airways are 8 miles wide to allow for the angular accuracy of VOR measurements, which is better than 4°. GPS will eventually replace VOR navigation, allowing aircraft to directly from point of origin to destination, but the system of VCR beacons in the ted States is likely to remain for many years as a backup to GPS.

GPS can provide a single navigation system with better accuracy and reliability than earlier radio navigation aids. It can provide navigation of aircraft directly between air-instead of indirectly via airways, while providing absolute position readout of latitude and longitude. Differential GPS can be used instead of ILS to provide the required straight line in the sky for an instrument approach to a runway, and can be linked to an pilot to provide automatic landing of aircraft in zero visibility conditions. Ships can safely navigate and dock in treacherous waters in bad weather by using differential GPS. Eventually, GPS will replace all other means of navigation, although some may be retained as backup systems in case of failure of the GPS receiver(s) or jamming of the signals.

GPS was preceded by an earlier satellite navigation system called Transit, built for U.S. Navy for ship navigation, which achieved much lower accuracy and became obsolete when GPS was introduced. Transit satellites were in low earth orbits and the system used the Doppler shift observed at the receiver when a beacon signal was transmitted by the satellite. Because of the high velocity of LEO satellites—about 7.5 km/s— their signals are significantly shifted up in frequency when the satellite appears over the horizon with a component of velocity toward the receiver. The Doppler shift falls to zero as the satellite passes the observer, and then becomes negative as the satellite flies away.

Observation of the Doppler shift with time, which may need to be as long as 10 min, and a knowledge of the satellite orbit, allows calculation of the receiver's position.

There was never a sufficient number of Transit satellites to provide continuous position data, and the long time required to obtain an accurate position fix was a disadvantage. A similar system called SARSAT, for search and rescue satellite, is used to find emergency locator transmitters (ELTs) on aircraft that have crashed. Most general aviation aircraft carry an ELT, which turns on at a frequency of 121.5 MHz when subjected to high G forces, as might be experienced if the aircraft crashes. Certain LEO satellites carry 121.5 -MHz receivers that relay the signals to earth stations at rescue coordination centers. If an aircraft ELT turns on, a SARSAT satellite will eventually fly by and relay a Doppler shifted signal to the rescue station. Analysis of the Doppler shift over the observation period provides information about the location of the ELT, but with an accuracy of only 1 or 2 km. Almost 97% of ELT locations turn out to be false alarms—the ELT was dropped or accidentally turned on. It seems probable that GPS and cellular phones or satellite phones will eventually replace the SARSAT system.

GPS POSITION LOCATION PRINCIPLES

The basic requirement of a satellite navigation system like GPS is that there must be four satellites transmitting suitably coded signals from known positions. Three satellites are required to provide the three distance measurements, and the fourth to remove receiver clock error. Figure 12.2 shows the general arrangement of position location with GPS. The three satellites provide distance information when the GPS receiver makes three measurements of range, Ri, from the receiver to three known points. Each distance Ri can be thought of as the radius of a sphere with a GPS satellite at its center. The receiver lies at the intersection of three such spheres, with a satellite at the center of each sphere. Locally, at the receiver, the spheres will appear to be planes since the radii of the spheres are very large. A basic principle of geometry is that the intersection of three planes completely defines a point. Thus three satellites, through measurement of their distances to the receiver, define the receiver location close to the earth's surface. There is another point in outer space where the three spheres intersect, but it is easily eliminated in the calculation process.

FIGURE-2:General arrangement of position locations with GPS. The aircraft must receive signals from four GPS satellites to be able to determine its position.

Although the principles by which GPS locates a receiver are very simple, requiring only the accurate Measurement of three ranges to three satellites implementing the measurement with the required accuracy is quite complex. We will look first at the way in which range is measured in a GPS receiver and then consider how to make the measurements. Range is calculated from the time delay incurred by the satellite signal in traveling from the satellite to the GPS receiver, using the known velocity of EM waves in free space. To measure the time delay, we must know the precise instant at which the signal was transmitted, and we must have a clock in the receiver that is synchronized to the clock on the satellite.

GPS satellites each carry four atomic clocks which are calibrated against time standards in the GPS control stations around the world. The result is GPS time, a time standard that is available in every GPS satellite. The accuracy of an atomic clock is typically 1 part in 1011. However, it is too expensive to include an atomic clock in most GPS receivers, so a standard crystal oscillator with an accuracy of 1 in 105 or 1 in 106 is used instead. The receiver clock is allowed to have an offset relative to the GPS satellite clocks, so when a time delay measurement is made, the measurement will have an error caused by the clock offset.

For example, suppose the receiver clock has an offset of 10ms relative to GPS time. All distance measurements will then have an error of 3000 km. Clearly, we must have a way to remove the time error from the receiver clock before we can make accurate position measurements. C/A code receivers can synchronize their internal clocks to GPS time within 170 ns, corresponding to a distance measurement uncertainty of 50m.Repeated measurements and integration improve the position location error to well below 50 m.

It is surprisingly easy to remove the clock error, and this removal is one of the strengths of GPS. All that is needed is a time measurement from a fourth satellite. We need three time measurements to define the location of the receiver in the three unknown coordinates x, y, and z. When we add a fourth time measurement we can solve the basic position location equations for a fourth unknown, the receiver clock offset error τ. Thus the four unknowns in the calculation of the location of the receiver are x, y, z, and τ.

Position Location in GPS

First, we will define the coordinates of the GPS receiver and the GPS satellites in a rectangular coordinate system with its origin at the center of the earth. This is called the earth centered earth fixed (ECEF) coordinate system, and is part of the WGS-84 description of the earth. WGS-84 is an internationally agreed description of the earth's shape and parameters, derived from observations in many countries 4. GPS receivers use the WGS-84 parameters to calculate the orbits of the GPS satellites with the accuracy required for precise measurement of the range to the satellites. The Z-axis of the coordinate system is directed through the earth's North Pole and the X-and Y-axes are in the equatorial plane. The X-axis passes through the Greenwich meridian—the line of zero longitude on the earth's surface, and the Y-axis passes through the 90° east meridian. The ECEF coordinate system rotates with the earth. The receiver coordinates are (Ux, Uy, Uz),and the four satellites have coordinates

(Xi, Yi, Zi), where I = 1, 2, 3, 4. There may be more than four satellite signals available, but we use only four signals in a position calculation. The measured distance to satellite is called a psuedorange, PR,, because it uses the internal clock of the receiver to make a timing measurement that includes errors caused by receiver clock offset. The geometry of a GPS measurement is illustrated in Figure-3.

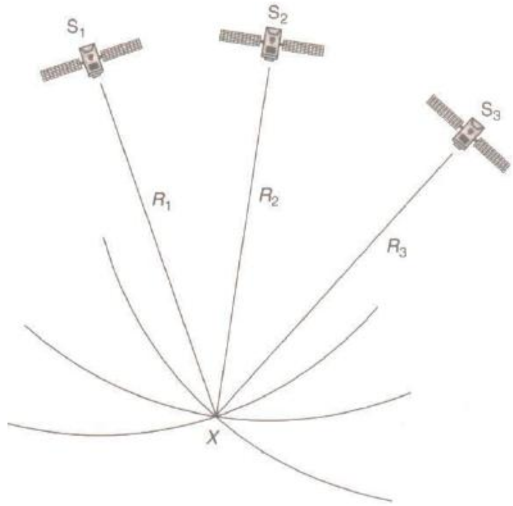


FIGURE-3: Position location by measurement of the distance to three satellites. The GPS receiver is located at point X, where three spheres with radii R1, R2, and R3 intersect. The centers of the spheres are the three GPS satellites S1, S2, and S3. If the distances R,, R2, and R3 are measured, the location of the point X can be uniquely defined.

Psuedorange, denoted as PR,, is measured from the propagation time delay T_i between the satellite (number i) and the GPS receiver, assuming that EM waves travel with velocity c.

$$PR_i = T_i \times C$$

The distance R between two points A and B in a rectangular coordinate system is given by

$$R^2 = (x_A - x_B)^2 + (y_A - y_B)^2 + (z_A - z_B)^2$$

The equations which relate pseudorange to time delay are called ranging equations:

$$(X_1 - U_x)^2 + (Y_1 - U_y)^2 + (Z_1 - U_z)^2 = (PR_1 - \tau c)^2$$
$$(X_2 - U_x)^2 + (Y_2 - U_y)^2 + (Z_2 - U_z)^2 = (PR_2 - \tau c)^2$$
$$(X_3 - U_x)^2 + (Y_3 - U_y)^2 + (Z_3 - U_z)^2 = (PR_3 - \tau c)^2$$
$$(X_4 - U_x)^2 + (Y_4 - U_y)^2 + (Z_4 - U_z)^2 = (PR_4 - \tau c)^2$$

Where τ is receiver clock error (offset, or bias).

The position of the satellite at the instant it sent the timing signal (which is actually the start of a long sequence of bits) is obtained from ephemeris data transmitted along with the timing signals. Each satellite sends out a data stream that includes ephemeris data for itself and the adjacent satellites. The receiver calculates the coordinates of the satellite relative to the center of the earth, $(X_i Y_i, Z_i)$, and then solves the four ranging equations for the four unknowns using standard numerical techniques for the solution of nonlinear simultaneous equations. (The equations are nonlinear because of the squared terms.)

The four unknowns are the location of the GPS receiver, (Ux,Uy,Uz), relative to the center of the earth and the clock offset τ –called clock bias in GPS terminology. The receiver position is then referenced to the surface of the earth, and can be displayed in latitude, longitude, and elevation. Typical accuracy for a low-cost GPS receiver using the GPS C/A code is 30 m defined as a 2DRMS error. The term DRMS means the distance root mean square error of the measured position relative to the true position of the receiver. If the measurement errors are Gaussian distributed, as is often the case. 68% of the measured position results will be within a distance of 1DRMS from the true location and 95% of the results will be within 2DRMS of the true location. Accuracy in GPS measurements is usually defined in terms of 2DRMS, in the horizontal or vertical plane.

In practice, the error surface that encloses 68 or 95% of all measurements is not a circle but an ellipse, and the error in any dimension is affected by several dilution of precision (DOP) factors. DOP is discussed later in this chapter. The U.S. Department of Defense has the ability to degrade the position measurement accuracy of C/A code receivers by applying selective availability (SA). SA exists to allow the accuracy of C/A code receivers to be degraded in the event of a national emergency (i.e., enemy action) affecting the United States and was applied to the C/A signals most of the time until May2000. SA was switched off on May 1, 2000, and will not be used again unless the security of the United States is threatened. With SA off, the' accuracy of GPS position measurements with the C/A code increased dramatically, particularly in the vertical dimension. Variation in elevation readout of a typical C/A code receiver with SA on could be as large as 200 m. With SA off, the variation may be as small as 10 m.

Selective availability and atmospheric propagation effects (tropospheric and ionospheric) all cause errors in the timing measurements made by a GPS receiver, leading to position location errors. The atmosphere and the ionosphere introduce timing errors because the propagation velocity of the GPS signals deviates from the assumed free space value. The errors can be largely removed if a number of GPS reference stations are built at precisely known locations. The stations observe the GPS signals and compute the current error in position as calculated from GPS data. This information can then be broadcast to all GPS users as a set of corrections to be applied to GPS measurements. The system is called a wide area augmentation system(WAAS).

A network of 24 WAAS stations built in North America for the U.S. Federal Aviation Administration (FAA) provides aircraft with improved position measurement accuracy. Using WAAS, accuracies of a few meters can be obtained with C/A code receivers. In the event of a national emergency, WAAS would be switched off to prevent enemies using GPS for accurate targeting of weapons. WAAS also includes an integrity monitoring system to ensure that the GPS signals used by aircraft do not contain errors which could cause false readings. WAAS is required to send a warning of possible errors within 5.6 s if a problem is detected with any GPS satellite signal.

Similarly, a single reference station at a known location—for example, an airport— can determine the local measurement error in GPS and broadcast this information to GPS users so that greater accuracy can be obtained with a C/A code receiver. This is one (simple) form of differential GPS (DGPS). More complex forms of differential GPS use a reference station which transmits the signals received from each GPS satellite so that phase comparisons can be made by the receiver. With lengthy integration times and a sophisticated phase comparison receiver, differential GPS accuracies of 1 cm can be obtained. With DGPS, the receiver computes its position relative to the reference station rather than in latitude and longitude. Differential GPS is used when a vehicle needs to be positioned accurately with respect to a fixed point, such as an aircraft with respect to a runway or a ship with respect to a berth.

GPS Time

The clock bias value T which is found as part of the position location calculation process can be added to the GPS receiver clock time to yield a time measurement that is synchronized to the GPS time standard. The crystal oscillator used in the GPS receiver is highly stable over a period of a few seconds, but will have a frequency which changes with temperature and with time. Temperature changes cause the quartz crystal that is the frequency determining element of a crystal oscillator to expand or contract, and this changes the oscillator frequency.

Crystals also age, which causes the frequency to change with time. The changes are very small, but sufficient to cause errors in the clock time at the receiver when the clock is not synchronized to a satellite. Calculating the clock bias by solving ranging equations allows the receiver clock time to be updated every second or two so that the GPS receiver time readout is identical to GPS time.

Every GPS receiver is automatically synchronized to every other GPS receiver any- where in the world through GPS time. This makes every GPS receiver a super clock, which knows time more accurately than any other time standard. Prior to the widespread use of GPS receivers, standard time transmissions were broadcast by the U.S. National Institute of Science and Technology (NIST, formerly the Bureau of Standards). The broadcasts were made in the HF (shortwave) band, and could be received throughout the United States. However, the HF signals propagate over long distance by reflection from the ionosphere, which introduces an uncertain delay into the time of arrival of the signal. The time standard provided by GPS is typically accurate to better than 170 ns, and has been used to synchronize electric power generators across the United States, for scientific applications that require synchronized clocks in different locations, and as a long-term frequency standard.

The time standard on board each GPS satellite consists of two cesium clocks plus two rubidium clocks (atomic clocks). An atomic clock uses the fundamental resonance of the cesium or rubidium molecule as a frequency reference to lock a crystal oscillator. In the GPS satellites, the master oscillator is at 10.23 MHz; all code rates, the Li, and the L2 RF frequencies are multiples or submultiples of 10.23 MHz. The atomic clocks are updated by the controlling ground stations to keep them within 1 As of Universal Time Coordinated (UTC), and the navigation message broadcast by each satellite contains information about its current clock errors relative to GPS time. (UTC is a worldwide time standard. Greenwich Mean Time (GMT) is equal to UTC.)

GPS RECEIVERS AND CODES

GPS satellites transmit using pseudorandom sequence (PN) codes. All satellites transmit a C/A code at the same carrier frequency, 1575.42 MHz, called Li, using BPSK modulation. The Li frequency is 154 times the master clock frequency of 10.23 MHz. The C/A code has a clock rate of 1.023 MHz and the C/A code sequence has 1023 bits, so the PN sequence lasts exactly 1.0 ms. The exact values of the frequencies are about 0.005 Hz lower than stated here to allow for relativistic effects caused by the high velocity of the satellites in their orbits (3.865 km/s). (GPS measurements are one of the few examples where relativistic effects must be taken into account, because the clocks are mounted on platforms moving at very high speeds.) The P code is transmitted using BPSK modulation at the L2 carrier frequency of 1227.6 MHz (120 X 10.23 MHz), and is also transmitted with BPSK modulation on the Li carrier frequency, in phase quadrature with the C/A code BPSK modulation. Figure 12.4 shows the way in which the Li and L2 signals are generated on board a GPS satellite. The C/A and P code transmissions from all GPS satellites are overlaid in the Li and L2 frequency bands, making GPS a direct sequence spread spectrum (DS -SS) system.

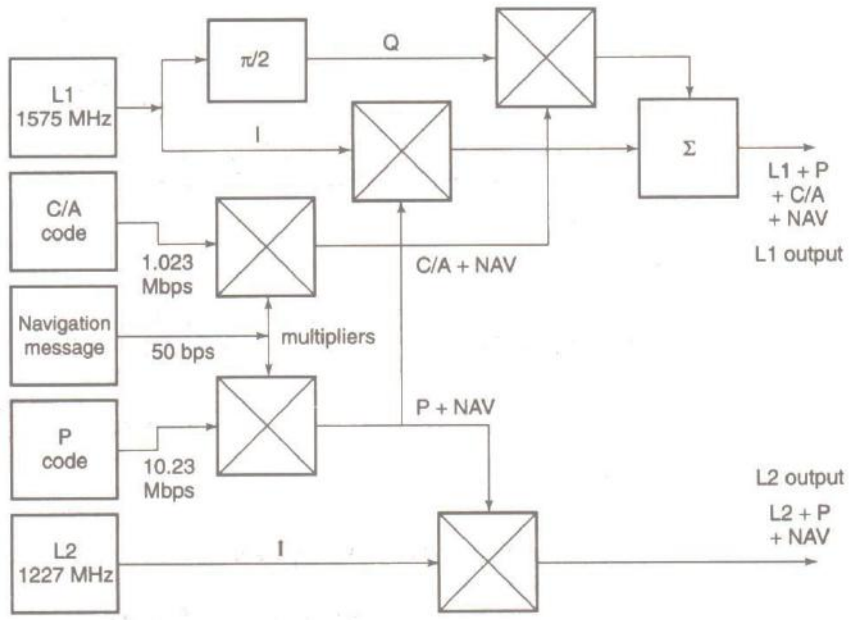


FIGURE-Signal generation in a GPS satellite.

The receiver separates signals from individual GPS satellites using knowledge of the unique C/A code that is allocated to each satellite. At most, 12 GPS satellites can be seen by a receiver at any one time, so the coding gain in the spread spectrum receiver must be sufficient to overcome the interference created By 11 unwanted signals while recovering the twelfth wanted signal.

The C/A Code

The C/A codes transmitted by GPS satellites are all 1023 bit Gold codes. GPS C/A Gold codes are formed from two 1023 bit in -sequences, called G1 and G2, by multi- plying together the G1 and G2 sequences with different time offsets. An m -sequence is a maximum length pseudorandom (PN) sequence, which is easy to generate with a shift register and feedback taps. A shift register with n stages can generate a PN sequence 2 — 1 bits in length. The bit pattern is set by the feedback taps and combining logic of the shift register. The PN sequences G1 and G2 are both generated by 10 -bit shift registers and are therefore both 1023 bits long. The clock rate for the C/A code is 1.023 MHz, so each sequence lasts 1.0 ms. Figure 12.5 shows a generator diagram for the C/A code.

The C/A code for a particular satellite is created with an algorithm that includes the identification number of the GPS satellite, thus creating a unique code for each satellite_ The satellite with ID number ***i*** has a C/A code sequence Ci (t)

$$Ci(t) = G1(t) \times G2(t + 10iTc) \qquad (12.4)$$

where T c= clock period for the C/A code.

There are 64 Gold sequences available for satellites numbered 1 through 64. A total of 100 Gold sequences can be created using the algorithm in Eq. (12.4), but not all the sequences have sufficiently low cross -correlation properties, and reference 4 states that 37 are actually used in the GPS system. Low cross -correlation of the sequences is a requirement because the GPS receiver can pick up signals from as many as 12 satellites at the same time.

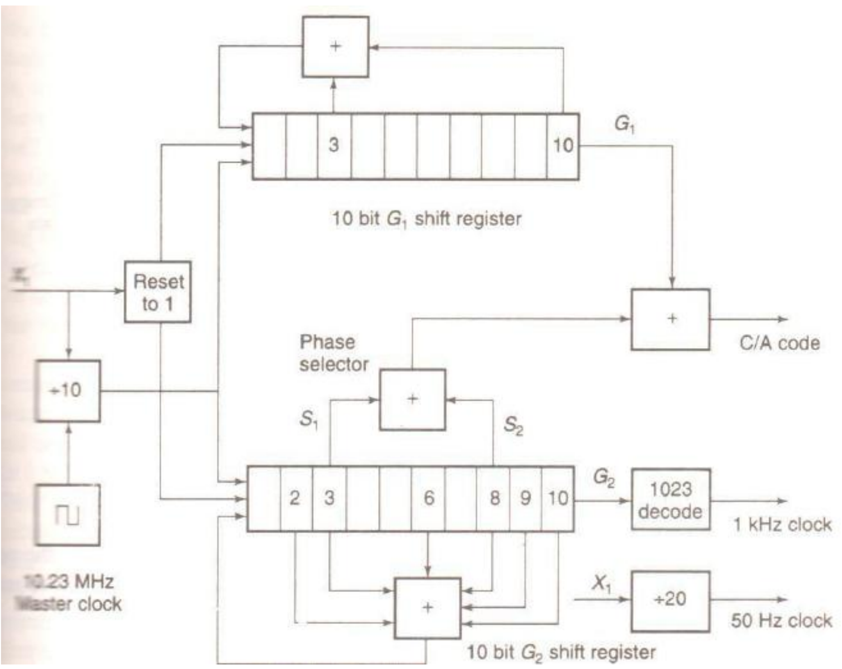


FIGURE- C/A code generator.

A correlator in the receiver looks for one of the sequences and must reject all other sequences that are present. Two C/A code sequences with zero cross -correlation would achieve a rejection ratio of 1023, but the 64 available C/A code sequences will not all have zero cross -correlation. The selected group of 37 are the sequences with the lowest levels of cross -correlation among the available set of 100 Gold code sequences. They also have low autocorrelation time sidelobes, another requirement of direct sequence spread spectrum systems.

The C/A code sequence length of 1.000 ms gives range ambiguity of 300 km, since the code travels at a velocity of approximately 3 x 10^8 m/s and therefore has a length in space of 3x10^5m. The entire C/A code sequence repeats in space every 300 km, leading to ambiguity of position only if the GPS receiver is in outer space, The ambiguity easily resolved if the receiver knows roughly where it is; just knowing that the receiver is located close to the earth's surface is usually sufficient. The user can enter the approximate location of the GPS receiver when it is first switched on to help resolve any ambiguities quickly.

The above figure shows a simplified block diagram of a C/A code GPS receiver. The antenna is typically a circularly polarized patch antenna with an LNA mounted on the printed circuit board. A conventional superhet receiver is used to generate an IF signal in a bandwidth of about 2 MHz, which is sampled using / and Q sampling techniques and processed digitally. The digital portion of the receiver includes a C/A code generator, a correlator, and a microprocessor that makes the timing measurements and calculates the receiver's position. Most GPS receivers make use of a 12 -channel IC chip set that can be purchased for about $25.00 (Year 2000 prices).

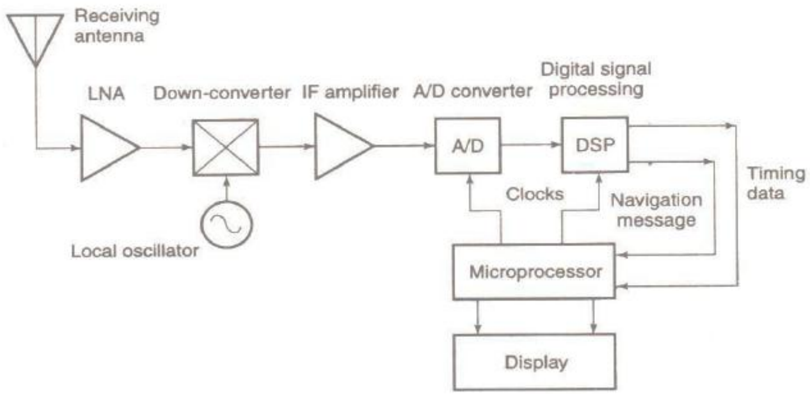


FIGURE -Simplified GPS receiver.

SATELLITE SIGNAL ACQUISITION

The GPS receiver must find the starting time of the unique C/A code for each of four satellites. This is done by correlating the received signal with stored C/A codes, as in any direct sequence spread spectrum system. (See Chapter 6 for details of this process.) Usually, the receiver will automatically select the four strongest signals and correlate to those. If the geometry of the strongest satellites is poor, that is, the satellites are close together and have pseudoranges that are nearly equal, the receiver may also use several weaker signals. If the receiver is making a cold start, with no information about the current position of GPS satellites, or its own location, it must search all 37 possible C/A codes until it can correlate with one. Once correlation is obtained, the data stream (called the navigation message) from that satellite can be read by the receiver. The data stream contains information about the adjacent satellites, so once one signal is correlated, the receiver no longer needs to search through all the other 36 possible codes to find the next satellite; it can go directly to the correct code. Searching all 36 C/A codes of 1023 bits for correlation can be a slow process. In the worst case, 36 codes might have to be searched before a correlation could be obtained. However, available satellites in 2000 all had numbers between 13 and 455, so, on average, 16 codes might have to be searched before correlation is successful.

A direct sequence spread spectrum receiver locks to a given code by matching the locally generated code to the code received from the wanted satellite. Since the start time of the code transmitted by the satellite is not known when the receiver commences the locking process, an arbitrary start point must be selected. The locally generated code is compared to the received code, bit by bit, through all 1023 bits of the sequence, until either lock is found, or the receiver concludes that this is not the correct code for the satellite signal it is receiving.

If the starting time for the locally generated code was not selected correctly, correlation will not be obtained immediately. (This will occur with a probability of 99.9% when the timing of the locally generated sequence is selected at random.) The locally generated code is then moved forward one bit in time, and correlation is attempted again. The process is continued 1023 times until all possible starting times for the locally generated code have been tried. If the satellite with that particular C/A code is not visible, no correlation will occur and lock will not be achieved. It takes a minimum of 1 s to search all 1023 bit positions of a 1023 bit C/A code, so in a typical case, it will take at least 15 s to acquire the first satellite. Many receivers search for a given C/A code several times before moving to the next code, so several minutes may elapse before the correct C/A code is found, given no other information. Once one C/A code is found, the remaining satellites can then be acquired in a few seconds because their IDs are known from the data transmitted in the navigation message of each satellite.

Although it takes only 20 s on average to lock to the C/A code of one satellite, the receiver must find the Doppler frequency offset for at least one satellite before correlation can occur. The receiver bandwidth is matched to the bandwidth of the C/A code. The theoretical noise bandwidth of the C/A code receiver is 1.023 MHz and the velocity of the satellites is 3.865 km/s. The angle between the spacecraft velocity vector and a receiver on earth is 76.10 when a GPS satellite is at the horizon, so the maximum velocity component toward a receiver is 2), = 928 in/s, giving a maximum Doppler shift in the Li signal of vr /A = 4.872 kHz, ignoring the effect of earth rotation. Allowing the satellite to reach an elevation angle of 5° before it is used for a position measurement limits the Doppler shift that must be accommodated by the receiver to - ±4 kHz_ From a cold start, the receiver must try eight Doppler frequency shifts of up to - ±4 kHz in 13Hz steps when searching for the signal from a satellite. This can increase the acquisition time of the first satellite to several minutes. Figure below illustrates the search process. There are eight possible Doppler shifts for each signal, and 1023 possible code positions, giving 8184 possible signal states that must be searched.

Once any of the GPS satellites has been acquired, the navigation message provides sufficient information about the adjacent satellites for the remaining visible satellites to be acquired quickly. The receiver may need to search in Doppler shift because the position of the receiver relative to the satellites is not known, but their C/A codes are. The GPS receiver retains the information from the navigation message when switched off, and it also runs its internal clock. When next switched on, the receiver will assume that its position is close to its last known position when it was switched off, calculate which satellites should be visible, and search for those first. This greatly speeds up the acquisition process. If the receiver has been moved a large distance while turned off, a cold start may be needed.

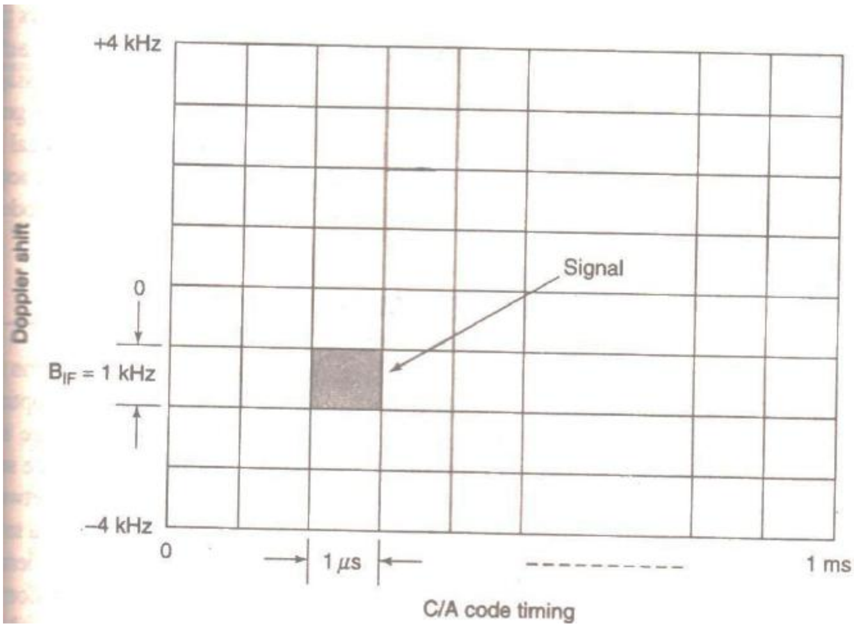


FIGURE-Code synchronization and doppler tracking matrix

The correlation process described above assumes that each satellite is acquired sequentially. Some lower cost GPS receivers use sequential acquisition of the satellites, and also make timing measurements sequentially, one satellite at a time. More sophisticated receivers have parallel correlators which can search for and acquire satellites in parallel. Twelve parallel correlators guarantee that all visible GPS satellites will be acquired, and start-up time is much shorter than with sequential acquisition. Accuracy is also better with parallel processing of the signals.

Integrity monitoring of the GPS position measurement is possible by using a fifth satellite to recalculate the receiver position. With five satellite signals there are five possible ways to select four pseudoranges to use in the ranging equations, leading to five calculations of position. If there is disagreement between the results, one bad measurement can be eliminated. If more than one result disagrees with the others, the integrity of the measurements is compromised. GPS receivers used for navigation of aircraft in instrument meteorological conditions (IMC, in the clouds) and for instrument landings are required to have integrity monitoring to guard against receiver or satellite failures and interference with or jamming of GPS signals.

The P code for the ith satellite is generated in a similar way to the C/A code. The algorithm is

$$Pi(t) = X1(t) + X2(t + iT_c) \quad (12.5)$$

where T c is the period of the X1 sequence, which contains 15,345,000 bits and repeats every 1.5 s. The X2 sequence is 37 bits longer. The P code repeats after 266.4 days, but is changed every 7 days for security reasons. The long length of the P code sequence makes the distance measurements unambiguous. P code sequences cannot be acquired easily because they do not repeat, a deliberate feature to prevent unauthorized users from operating high accuracy GPS receivers. The C7A code provides information to authorized users on the starting time of the P code; this is contained in the navigation message as an encrypted handover word. If the current feedback tap settings for the P code generators are known, and the handover word is decrypted, the receiver can start the local X Code generators close to the correct point in the P code sequence. This allows rapid acquisition of the P code, and is the origin of the name coarse acquisition for the C/A code.

GPS NAVIGATION MESSAGE

A key feature of the GPS C/A code is the navigation message. The navigation message contains a large amount of information that is used by GPS receivers to optimize the acquisition of satellite signals and calculate position. The navigation message is sent at 50 bps by BPSK modulation of the C/A and P codes. Effectively, 20 C/A code sequences form one navigation message bit. The phase of the 20 sequences is inverted between the 1 and 0 bits of the message by modulo -2 addition of the navigation message data to the C/A and P code sequences. The navigation signal is extracted by a 50 -bps BPSK demodulator that follows the C/A or P code correlator. The narrow bandwidth of the navigation message ensures a high S/N ratio at the demodulator input and correspondingly low probability of

TABLE 12.1 GPS Navigation Message: Subframe Details

Header	Telemetry message: health of satellite, handover word
Subframe 1	Satellite clock correction data. Age of transmitted data
Subframe 2 and 3	Ephemeris for this satellite
Subframe 4	Almanac data for satellites 25 and higher. Ionospheric model data
Subframe 5	Almanac data for satellites 1–24. Health data for satellite 1–24

Note: Subframes 1, 2, and 3 repeat all data every 30 s. Subframes 4 and 5 repeat every 30 s, but transmission of the full data set requires 25 subframes over a period of 12.5 min.

bit errors in the navigation message. Satellites with elevation angles above 10^0 will typically give a S/N ratio of greater than 17 dB at the output of the correlator. The complete navigation message is 1500 bits, sent as a 30-s frame with 5 subframes. However, some information is contained in a sequence of frames, and the complete data set requires 12.5 min for transmission. The most important elements of the message are repeated in every frame. The subframes contain the satellite's clock time data, orbital ephemeris for the satellite and its neighbors, and various correction factors. Details of the subframes are given in Table 12.1.

The calculation of position in a GPS receiver requires very accurate knowledge of the location of the satellite at the time that the measurements of pseudoranges are made. If the pseudorange is measured to an accuracy of 2.4 m, we must know the satellite position to an even greater accuracy, and that requires very accurate calculation of the GPS satellite orbits. By comparison, the orbit of a communication satellite does not need to be known to the same level of accuracy. As described in Chapter 2, the GPS system uses modified WGS-84 data to define the earth's radius, Kepler's constant, and the earth's rotational rate. Data on the speed of EM waves is taken from the International Astronomical Union. The WGS-84 data set also includes a very detailed description of the earth's gravitational field, which is essential for precise location of the satellites in their orbits. All of these parameters and corrections are stored in every GPS receiver, and used in calculating position.

GPS SIGNAL LEVELS

GPS receiver antennas have low gain because they must be omnidirectional. We will assume a worst -case gain of G = 0 dB, corresponding to an isotropic antenna. In practice, G> 0 dB in many directions, but may fall to 0 dB in some directions. The omnidirectional antenna picks up radiated noise from the environment, making the antenna temperature close to 273 K. LNA temperatures can be as low as 25 K, so a system noise temperature of 273 K will be used as a typical value. Typical GPS antennas are circularly polarized patches or quadrafilar helices that have carefully shaped patterns that cut off quickly below 10° elevation to minimize noise pick up from the ground. The LNA is mounted directly below or behind the antenna to avoid the increase in noise temperature caused by lossy antenna cables.

GPS satellites have an array of helical antennas that provide gain toward the earth, and 10 W transmitters, leading to EIRP values in the range 19 to 27 dBW. The C/A code transmitted by the satellite is a direct sequence spread spectrum signal, so the C/N ratio in the C/A code's RF bandwidth will be less than 0 dB. This is typical of systems that use direct sequence spread spectrum signals. The low C/N ratio of the spread spectrum signal is converted to a usable S/N by correlation of the code sequences, which adds a despreading (processing) gain to the C/N ratio. The theoretical processing gain of a direct sequence spread spectrum signal is equal to the ratio of the chip rate to the bit rate in the spreading sequence, but losses in the correlation process always make practical gains a little lower. For the C/A code transmitted at 1.023 Mbps and a 1 -ms correlation time, the theoretical processing gain is 1023, or 30.1 dB. The corresponding processing gain for the P code is 40.1 dB.

The GPS receiver can pick up signals from up to 10 satellites at the same time. The RF energy from the satellite spread spectrum transmissions adds to the noise in the receiver as an interference term, I. For simplicity, in the following analysis we will assume that there are 10 GPS satellites visible, that there are 9 interfering satellites generating random signals (noise) out of which the receiver must extract the 10th signal, and that all the received signals are of equal strength. The signals from interfering satellites are treated as random noise because the Gold codes that they transmit have very low cross –correlation with the code from the wanted satellite. Noise has zero cross -correlation with the wanted signal, and the Gold codes used by GPS satellites are chosen because they closely approximate noise.

Nine interfering GPS satellites represents a worst case; in practice the number of visible satellites varies between four and ten, and the signal strengths also vary depending on the elevation angle of the satellite and the antenna pattern at the receiver. The worst case is actually when a weak signal from a satellite at a low elevation angle must be extracted from stronger signals from satellites at higher elevation angles. GPS receivers automatically select the strongest signals for processing so that the worst case can be avoided, but if the sky is partially blocked by obstructions, a weak signal may have to be used.

TIMING ACCURACY

The position location process requires an accurate measurement of the time of arrival of the code sequence at the receiver. The output of the C/A code correlator is a 1 kts wide pulse that repeats every millisecond. The accuracy with which a timing measurement can be made on a single pulse is given by the approximate

$$\delta t \approx \frac{1}{[B_n \sqrt{S/N}]} \quad \text{seconds} \qquad (12.7)$$

Where St is the rms timing error, Bn, is the noise bandwidth of the RF channel, and S/N ratio is the signal-to-noise power ratio (not in dB) for the pulse in the noise bandwidth Bn.

The S/N ratio after the correlator is

S/N = C/N + Gp — losses (12.8)

Where Gp is the correlator processing gain. For the C/A code Gp = 1023 = 30.1 dB and

S/N = —19.3 + 30.1 dB — losses

= 11.7 dB — losses

If we assume the specification value for S/N of 11.7 dB and losses of 1.7 dB, S/N = 10 dB, a power ratio of 10. The theoretical noise bandwidth of the correlator is = 1 MHz (IF noise bandwidth) so

$$\delta t \approx 1/[10^6 \sqrt{10}]\,\text{s} = 0.316\ \mu\text{s} \qquad (12.9)$$

A typical GPS receiver will update the display no more than twice a second, so the pulses from the correlator can be averaged over a period of half a second, which will decrease the rms error by V500 = 22.4 to an rms value of 14 ns, assuming randomly distributed errors. The 14 ns rms timing error translates to an rms distance error of 4.2 m. However, four distance measurements are needed to obtain a position measurement, so with no other errors accounted for, the basic position measurement accuracy of the C/A code receiver is about 8.4 m (4.2 x Vi) measured as an rms value. A higher C/N ratio in the receiver will improve the accuracy, but other errors, discussed later in Section 12.10, will lower the accuracy.

The accuracy achieved by commercial C/A code GPS receivers was better than expected by the designers of the GPS system. Military strategists became concerned that C/A code GPS receivers could be used to target weapons against the United States with considerable accuracy. The U.S. Department of Defense (DOD) introduces selective availability (SA), a scheme to deliberately degrade the accuracy of C/A code receivers by varying some of the parameters of the GPS satellites. Selective availability was switched off on May 1, 2000, and will be turned on only if the security of the United States is threatened.

GPS RECEIVER OPERATION

A C/A code GPS receiver must be able to correlate signals from at least four satellites. Calculate time delays, read the Navigation message, calculate the Orbits of the GPS satellites, and calculate position from pseudoranges. The key to accurate position determination is accuracy in the timing of the arrival of the Gold code sequences from each satellite in view. All GPS receivers use a microprocessor to make the required calculations and to control the display of data. There are many different ways that this can be done, depending on the application for which the receiver is intended. The tasks of the microprocessor will not be considered here—it is assumed that once accurate timing data is available and the navigation Message read that the microprocessor can complete Its required tasks.

Most C/A code GPS receivers use an IC chip set that contains 12 parallel correlators. This allows the receiver to process signals from up to 12 satellites at the same time. Which helps keep all the signals synchronized? Some simpler receivers use a single correlator and process four satellite signals sequentially, with consequent lower accuracy. The received GPS signals are converted to a suitable IF frequency in the front end of the receiver, and then processed to recover the C/A codes. In more recent GPS receivers, much or all of the signal processing is done digitally using DSP techniques. The explanation of the signal processing techniques used in GPS receivers that follows is based on block diagrams that can be implemented in analog or digital form. The blocks presented in this discussion are those that would be found in an analog receiver. Most GPS receivers implement them using digital signal processing techniques (DSP). We will start the analysis by considering the signal received from the satellite at the output of the IF stage of the receiver.

The IF signal in the GPS receiver will consist of the sum of a number (up to 12) of signals from visible GPS satellites. The IF carrier signal has several BPSK modulations applied to it by the satellite, and when received on earth has been Doppler shifted by satellite and earth motion. The IF signal from N GPS satellites in view is

$$s(t) = \sum_{i=1}^{N} \{A_i C_i(t) D_i(t) \sin[(\omega_i + \omega_d)t - \phi_i(l_i) + \phi_i]\} \qquad (12.10)$$

where A_i is the amplitude of the received signal.

$C_i(t)$ is the Gold code modulation

$D_i(t)$ is the navigation message modulation

ω_i is the IF frequency of the received carrier

ω_d is the Doppler shift of the received signal

$\phi_i(l_i)$ is the phase shift along the path

ϕ_i is the phase angle of the transmitted signal

The key to successful measurements in a GPS C/A code receiver is to generate a signal in the receiver that is identical to the signal received from satellite i, but without the navigation data that is modulated onto the transmitted signal. When the correct signal is generated in the receiver it has the correct C/A code for satellite i, the code has the correct starting delay, and the correct Doppler shift has been applied. The locally generated signal is multiplied by the received signal, which contains several other signals from visible GPS satellites, and the output is integrated over the C/A code length of 1ms. The result is a constant output for a period of 20 ms, corresponding to duration of a navigation data bit. The precise matching of the locally generated signals to due received signals from four visible GPS satellites ensures that the local receiver's dip docks and C/A code generators are exactly in sync with the received signals. When this condition is achieved, the start time of each C/A code sequence and the corresponding chip clock transition provide the high accuracy time marker that makes GPS time delay measurement possible.

The receiver must measure $\varphi_i(l_i)$ in Eq. (12.10) as a time delay in order to obtain the pseudorange for each of the N satellites in view, and it most recover the $C_i(t)$ Modulation by correlation. The Di(t) modulation contains the navigation message as a 50 bps BPSK modulation of the $C_i(t)$ signal. Both the C(t) And D(t) signals are modulated onto the carrier of the satellite signal by binary phase shift keying and therefore have values ± -1. Demodulation of BPSK signals requires a locally generated carrier which is locked to the phase of the received carrier, and recovery of the data signal requires a bit clock that is locked to the bit rate of the received signal.

The wanted signal is buried below the receiver noise and CDMA interference. We must multiply the signal and noise by the wanted C/A code sequence to despread the signal and to bring it above the noise. The nominal bandwidth of the signal is 1 kHz after the correlator, since the 1023 bit sequence of the C/A code repeats every millisecond. However, the IF carrier can be shifted in frequency by up to 4 kHz because at Doppler effects. The receiver must therefore first search in Doppler frequency space—eight 1 kHz frequency offset steps—until a signal is found. This is done as part of die signal acquisition process by incrementing the frequency of the locally generated carrier in 1 kHz steps.

Part of a typical receiver structure for the GPS C/A code is shown in Figure 12.8. The function of the non -coherent delay lock loop is to set the frequency of the voltage controlled oscillator (VCO) in the receiver to match C/A code rate of the received signal, and to align the received chip transitions correctly. GPS satellites generate all their signals from a master clock, which means that there is phase coherence between the chips, the codes and the RF frequencies of all GPS signals from a particular satellite. The delay lock loop shown in Figure 12.8 takes advantage of the coherent nature of the GPS C/A signals, so that the VCO becomes both a time reference for the C/A code signals and also the chip clock. The PN code generator in Figure 12.8 must be set to the correct code, and its start time must also be set correctly, for the loop to lock_ When the IF C/A code in the receiver is correctly generated and has the correct frequency and timing, it will exactly match the received C/A code at the input to the delay lock loop.

The delay lock loop has three paths: punctual, early (half chip ahead), late (half chip behind). The delay lock loop steers the chip clock so that the punctual output can be used to drive the C/A code generator. The C/A code chip rate is generated by the VCO. The incremental process of trial and error which eventually finds the correct sequence and timing was described above. The early -late channels in the delay lock loop generate output signals winch steer the phase of the VCO so that the navigation message is recovered correctly.

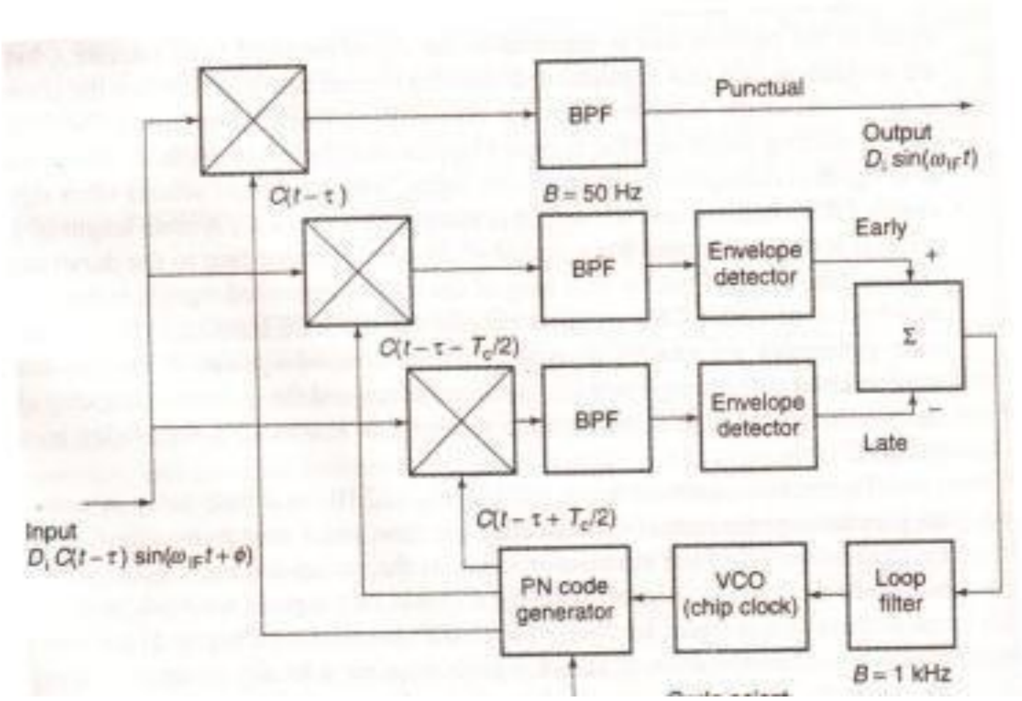


FIGURE 12.8;Noncoherent code lock loop and navigation message recovery. VCO, voltage controlled oscillator.

The locally generated carrier that is used to demodulate the C(t) signal must be Doppler shifted to match the Doppler offset of the received signal, and modulated with the correct C/A code sequence, starting at the correct time. The correct Doppler shift, code sequence, and start time are all unknown when the receiver is first switched on. The signal is buried below the noise, so it is not possible to determine the correct parameters by direct analysis of the received signal. The receiver must therefore be designed to search all possible Doppler shifts, code sequences, and code start times until an output is obtained from the correlator indicating that a satellite signal has been found. Once one GPS satellite signal has been found, information contained in the navigation message can be used to steer the receiver to the parameters needed to acquire the other visible satellites. If the receiver is turned off and then turned on again, the microprocessor memory has the last known satellite configuration stored, and can derive expected signal parameters by allowing for the time for which the receiver was off.

The output of the C/A code correlator with Doppler corrected IF frequency for the satellite signal with code number M is

$$x(t) = A_m R(\tau_m - \tau) D_m(t) \sin[\omega_m(t) - \phi_m(l_m) + \phi_m] + n(t) \qquad (12.11)$$

where R(τ_m — τ) is the autocorrelation function of the wanted code number M, and n(t) is the output from cross -correlation with all other codes.

The time shift (t_m — τ) to the correlation peak is the wanted measurement that provides the pseudorange to the satellite. The output of the correlator is a despread signal at baseband, which is modulated with the 50 bps navigation message. With the C/A code remo.ved,by the correlation process, it is a straightforward process to demodulate the navigation message D.

Passing this signal through a narrow bandwidth bandpass filter improves the S/N ratio and ensures that the message is recovered without errors. The IF carrier is recovered with a special type of phased locked loop (PLL) called a Costas loop. A Costas loop compensates for the arbitrary phase of the received signal.

The despread IF carrier is BPSK modulated by the navigation message D_m(t)

$$y(t) = A_m R(\tau_m - \tau) D_m(t) \sin[\omega_m(t) - \phi_m(l_m) + \phi_m] + n(t) \qquad (12.12)$$

The IF carrier signal is limited to remove any amplitude variations, which sets A, = 1. Then

$$y'(t) = R(\tau_m - \tau) D_m(t) \sin[\omega_m(t) - \phi'_m] + n(t) \qquad (12.13)$$

The navigation message D(t) is recovered by multiplying the IF signal y'(t) by sin[ω_m(t) – φ'm] And low pass filtering to obtain the 50 bps signal. The reference carrier for the BPSK demodulator can be derived from the output of the Costas loop. The demodulated message signal is z(t) where

$$z(t) = R(\tau_m - \tau) D_m(t) + n'(t) \qquad (12.14)$$

Provided that the correlation peak of z(t) crosses the threshold and n'(t) doesn't, we can recover the data message Dm(t) correctly. If everything works correctly in the receiver, the S/N of the signal y' (t) is at least 17 dB, so there will be no bit errors. Even if a bit error occurs in the navigation message, it is removed when the next message is received about 30 s later.

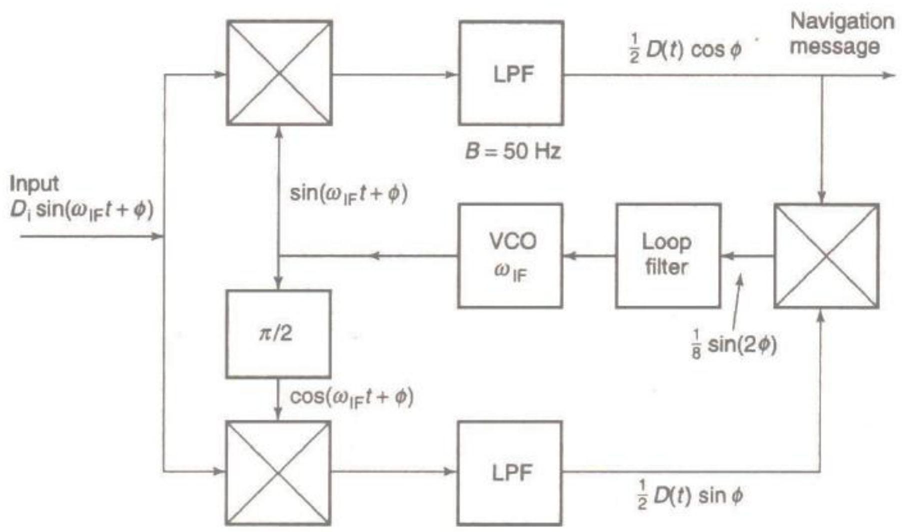


FIGURE 12.9 Costas loop. LPF, low pass filter.

Figure 12.9 shows a Costas loop which is often used as the demodulator for low speed BPSK signals such as the 50 bps GPS navigation message. The loop has an *I* channel and a Q channel driven by a VCO. The VCO frequency is set by the sum of the outputs from the *I* and

Q channel detectors, which steers the VCO phase such that the I channel is in phase with the signal. The *I* channel output is then (ideally) a zero ISI waveform which can be integrated and sampled to recover the navigation message bits.

GPS C/A CODE ACCURACY

The major sources of error in a GPS receiver that calculates its position are:
Satellite clock and ephemeris errors
Selective availability (when switched on)
Ionospheric delay (advance)
Tropospheric delay
Receiver noise
Multipath

The accuracy that can be achieved with a GPS C/A code receiver can be found by using a range error budget. The figures in square brackets [ ] are for the case when selective availability (SA) is turned off. Typical values of range error are given in Table 12.4. Al values are in meters (m). Note that a value of 2.4 m error is assigned to receiver noi The value calculated in Section 12.8 was 4.2 m, for a worst -case received signal strengtk_ The range error introduced by the ionosphere and the troposphere can be partially removed by receiving identical signals at two different carrier frequencies. This technique is used by high precision P code receivers. The P code signal is transmitted on the Li carrier at 1575.42 MHz, in phase quadrature with the C/A code signal. The P code is also transmitted on the L2 carrier at 1227.60 MHz. Algorithms are used in the P code receiver to calculate the net delay of the signal caused by the ionosphere and the atmosphere, and to then remove the errors from the calculated ranges. C/A code receivers use a standard atmosphere and ionosphere and assume a constant delay at a given elevation angle. Variations in the density of the atmosphere with atmospheric pressure changes, and in the free electron content of the ionosphere, lead to departure from the standard values nod hence to errors in the pseudorange calculation. There are plans to transmit the C A code a a third and a fourth L -band frequency from later GPS satellites to provide improved accuracy with C/A code receivers.

TABLE 12.4 Range Error for C/A Code Measurements (m)

Satellite clock error	3.5	
Ephemeris errors	4.3	
Selective availability	32.0	[0]
Ionospheric delay	6.4	
Tropospheric delay	2.0	
Receiver noise	2.4	
Multipath	3.0	
RMS range error	33.4 m with SA	
[RMS range error	9.5 m without SA]	

Brackets indicate SA off.

The range error shown in Table 12.4 is for one satellite—earth path, for the pseudo-range that is calculated from the timing measurements using the receiver clock_ However, four pseudorange measurements are needed to make a position determination. Thus the position location output of the GPS receiver combines four path errors, which are not necessarily equal because of the geometry of the satellites in the sky and the different signal strengths at the receiver input. Receiver position is calculated in (x, y, z) coordinates, and the errors in x, y, and z depend on the elevation angle of satellites, the satellite geometry, and the other parameters in the error budget. The calculated position will have different levels of error in the x, y, and z directions. To account for these differences several dilution of precision factors (DOP) are defined. A DOP factor multiplies the basic position measurement error to give a larger error caused by the particular DOP effect.

Dilution of Precision: HDOP, VDOP, and GDOP

Horizontal dilution of precision is one of the most important DOP factors for most GPS users. It provides an error metric for the x and y directions, in the horizontal plane. A typical HDOP value is 1.5, and it is often the smallest of the DOPs. Horizontal measurement error for a C/A code receiver is typically 14.3 m with SA off (1DR_MS) and 50 m with SA on (1DRMS). GPS practice uses 2DRMS as the quantifier for accuracy in position determination giving a 2DRMS accuracy of 28.6m with SA off_ The 2DRMS accuracy figure means that 95% of all measurements yield a position within 28.6 m of the true location of the GPS receiver, in this example.

There are many DOP factors in GPS. The more important ones are horizontal dilution of precision, HDOP, vertical dilution of precision, VDOR and geometric dilution of precision, GDOP. Other DOPs include position dilution of precision, PDOP, and time dilution of precision, TDOP. In general, VDOP and GDOP are most likely to degrade the accuracy of GPS position measurements. VDOP accounts for loss of accuracy in the vertical direction caused by the angles at which the satellites being used for the position measurement are seen in the sky. If the satellites are all close to the horizon, the angles between the satellites and the receiver are all similar and VDOP can be large. In the worst possible case, if all the satellites were at the horizon, it would be impossible to make an accurate measurement in the vertical direction. A change in range to at least one satellite must occur when the receiver is moved, otherwise the receiver cannot detect that change. If all the satellites are at the horizon, no range change occurs for vertical movement of the receiver and consequently vertical accuracy is very poor. Similarly, if all the satellites were clustered directly overhead, HDOP would be large. VDOP is important in aircraft position measurements, where height above the ground is a critical factor, especially when landing. C/A code receivers suffer from significant VDOP and cannot provide sufficient vertical accuracy for automated landing of aircraft. C/A code GPS receivers cannot guarantee sufficient vertical accuracy unless operated in a differential GPS mode. The GPS satellites are configured in orbit to minimize the probability that a DOP can become large, by arranging the orbits to provide clusters of four satellites with suitable spacings in the sky. However, if the receiver's view of the sky is restricted, for example, by buildings, the geometry for the position calculation may not be ideal and GDOP can become large. This causes all the other DOP values to increase. Aircraft, and ships at sea always have a clear view of the sky, but automobiles often do not. C/A code receivers may revert to two-dimensional measurements (x and y) using three satellites when the sky is obstructed.

DIFFERENTIAL GPS

The accuracy of GPS measurements can be increased considerably by using differential GPS (DGPS) techniques. There are several forms of DGPS, all of which are intended to increase the accuracy of a basic GPS position measurement, and to remove the effects of selective availability. A second, fixed, GPS receiver at a reference station is always required in a differential GPS system. In the simplest forms of DGPS, a second GPS receiver at a known position continuously calculates its position using the GPS C/A code. The calculated (x,y, z) location is compared to the known location of the station and the differences in x, y, and z are sent by a radio telemetry link to the first GPS receiver. The accuracy of the C/A code position measurement can be increased from 100 m to about 10 m, with SA in effect, but this technique works well only if the two stations are close together and use the same four satellites for the position calculation.

In a more sophisticated form of differential GPS, the monitoring station at a known location measures the error in pseudorange to each satellite that is visible at its location, and telemeters the error values to users in that area. This allows other GPS users to select which satellites they want to observe, and extends the area over which the DGPS system can operate. The accuracy of a C/A code measurement can be increased to 5 m for receivers within 10 km of the reference station and to 10 m for receivers within 500 km of the reference station.

The most accurate forms of differential GPS use the relative phase of the many signals in the GPS transmissions to increase the accuracy of the timing measurements. Suppose that you could count the number of cycles of the 1575 MHz Li carrier wave between a satellite and a GPS receiver, and that the GPS satellites are stationary for the length of time it takes to make the count at two separate locations. The wavelength of the L1 carrier is 0.19043 m, so movement of the receiver by 0.01 m directly away from the satellite would change the phase angle of the received wave by 18.9°. If the total number of cycles between the satellite and the receiver is known, and fractional cycles are measured with a phase resolution of 20°, the true distance to the satellite can be found to 0.01 m accuracy. In principle, measurements which compare the phase angle of the received Li carriers from several GPS satellites could therefore be used to detect receiver movements at the centimeter level. This is called differential phase or kinematic DGPS.

The obvious difficulty is that we cannot count the number of cycles of the Li carrier between the satellite and the receiver. However, we can make phase measurements and time of arrival comparisons for various GPS signals at two different locations and resolve motion between the two locations. If one of the receivers is a fixed reference station, it is then possible to locate the second GPS receiver very accurately with respect to that fixed location. This technique is valuable in land surveying, for example, where a reference station can be set up at a known location, such as the corner of a plot of land, and the position of the plot boundary relative to that point can be measured. The same technique can be used to find the position of an aircraft relative to an airport runway so that a precision approach path can be established. The difficulty with DGPS phase comparison measurements is that the L1 carrier has cycles which repeat every 0.19043 m, and one cycle is identical to the next. This creates range ambiguity which must be resolved by reference to the wavelengths of other signals. The 10.23 MHz P code transmission of the Li carrier has a P code chip length 1 in space of 29.326 m, which is 154 cycles of the Li carrier. The ambiguity of the carrier waveform can be resolved within the 29.326 m length of a P code chip by comparison of the time of arrival of a particular cycle of the Li carrier with the time since the start of the P code chip. Similar ambiguity resolution for the 29-m P code chips is possible using the length of the C/A code chip and the C/A code sequence. The length of a C/A code chip at 1.023 MHz is 293.255 m, and the length of a C/A code sequence is 293.255 km.

When ambiguity resolution is applied using all of these waveforms, very small movements of the receiver can be detected and ambiguity out to 293 km can be removed. Aircraft flight paths have been tracked to an accuracy of 2 cm over distances of tens of kilometres using phase comparison DGPS techniques.

This explanation of kinematic differential GPS is oversimplified, because the satellites are moving and measurements over a considerable Time are required to resolve ambiguity to the centimeter level. The P code can be used for real-time differential measurements without knowledge of P code itself, because only a comparison of the time of arrival of the code bits is required. Selective availability is not applied to the P code, so differential measurements made with the P code cannot be affected by SA. In the Wide Area Augmentation System (WAAS) developed by the FAA for aircraft Flying in North America, 24 WAAS receive stations continuously monitor their position as calculated from the C/A codes of all visible satellites in the GPS system. The stations also use the P code transmissions to make accurate differential measurements of the pseudorange to each visible satellite. The actual position of the WAAS stations is known very accurately from prior survey data, so each WAAS station can calculate the error in the pseudorange to each visible satellite. The 24 WAAS stations send their data to a central station with an uplink to a GEO satellite. The central station validates the data, combines all the information, and sends a sequence of pseudorange correction data to all GPS users via the satellite. The central station also determines whether any of the data is in error, and sends a warning signal called an integrity message to instruct aircraft not to use the GPS system, or a particular satellite, because the data are not reliable. This is an essential part of the FAA strategy for using GPS as the primary means of aircraft navigation. If the aircraft is relying on GPS information alone to determine its position, that information must have a very high reliability.

The WAAS GEO satellite transmits signals which are in a similar format to the L1 signals transmitted by a GPS satellite. A conventional GPS receiver with suitable software can extract the pseudorange error values from the WAAS satellite transmission and obtain markedly improved accuracy in its position determination. Thus no hardware changes are needed to convert a GPS receiver to use WAAS data. The GEO satellite can also be used to augment GPS satellites for position measurements, since it radiates the same signal format. The calculation of pseudorange error from the P code sequence, rather than (x,y,z) position data error from the C/A code, significantly increases the accuracy of the WAAS DGPS system.

Eventually, it seems probable that local area augmentation systems (LAAS) Using differential GPS will be established at many airports to replace or augment existing ILS precision approach systems. Advanced LAAS DGPS systems have been demonstrated to achieve better than 1-m accuracy in three dimensions, with update rates sufficiently fait to control a passenger aircraft. This is sufficient to allow DGPS position data to be coupled to the aircraft autopilot so that blind landings can be made automatically in zero visibility conditions. Several demonstrations of autoland using DGPS were made in the late 1990s using Boeing 737 and 757 aircraft.

Aircraft used by overnight delivery companies will likely be fitted with GPS big landing systems first, since cargo aircraft are subject to fewer restrictions than passenger aircraft and overnight delivery is subject to delays when airports are closed by low viability weather. Typically, a good autoland system fitted to a large aircraft can achieve more consistent landings than a skilled pilot, so autoland may eventually become as comma for landings as autopilot use is for en route operation. Weather may eventually be less of a factor in causing delays to passenger aircraft arrivals and departures.

TEXT BOOKS:

1. Satellite communications-Timothy Pratt, Charles Bostian and Jeremy Allnutt, WSE, Wiley Publications, 2nd Edition,2003.
2. Satellite communications Engineering-Wilbur L.Pritchard, Robert A Nelson and Henri G.Suyderhoud, 2nd Edition, Pearson Publications, 2003.

REFERENCES:

1. Satellite communications - Design Principles-M.Richharia, BS Publications, 2nd Edition, 2003.

UNIT V
SATELLITE APPLICATIONS

INTELSAT Series:

INTELSAT stands for *International Telecommunications Satellite.* The organization was created in 1964 and currently has over 140 member countries and more than 40 investing entities (see http://www.intelsat.com/ for more details).

In July 2001 INTELSAT became a private company and in May 2002 the company began providing end-to-end solutions through a network of teleports, leased fiber, and *points of presence* (PoPs) around the globe.

Starting with the Early Bird satellite in 1965, a succes- sion of satellites has been launched at intervals of a few years. Figure 1.1 illustrates the evolution of some of the INTELSAT satellites. As the figure shows, the capacity, in terms of number of voice channels, increased dramatically with each succeeding launch, as well as the design lifetime.

These satellites are in *geostationary orbit,* meaning that they appear to be stationary in relation to the earth. At this point it may be noted that geosta-tionary satellites orbit in the earth's equatorial plane and their position is specified by their longitude.

For international traffic, INTELSAT covers three main regions—the *Atlantic Ocean Region* (AOR), the *Indian Ocean Region* (IOR), and the *Pacific Ocean Region* (POR) and what is termed *Intelsat America's Region*.

For the ocean regions the satellites are positioned in geostationary orbit above the particular ocean, where they provide a transoceanic telecommunications

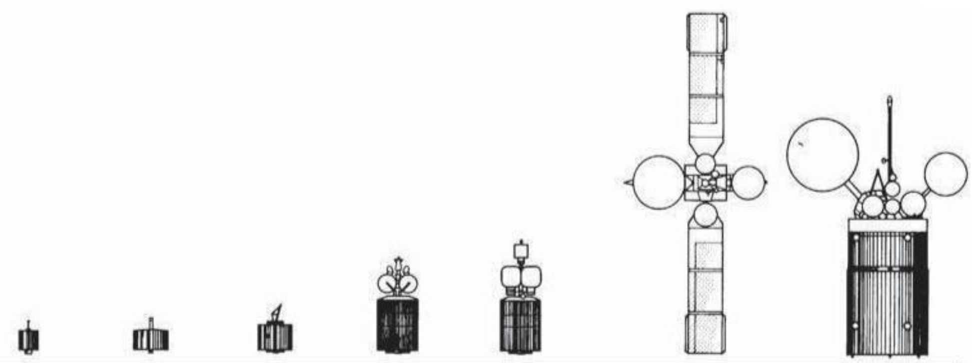
route. For example, INTELSAT satellite 905 is positioned at 335.5° east longitude. The

INTELSAT VII-VII/A series was launched over a period from October 1993 to June 1996. The construction is similar to that for the V and VA/VB series, shown in Fig. in that the VII series has solar sails rather than a cylindrical body.

The VII series was planned for service in the POR and also for some of the less demanding services in the AOR. The antenna beam coverage is appropriate for that of the POR. Figure 1.3 shows the antenna beam footprints for the C-band hemispheric cover- age and zone coverage, as well as the spot beam coverage possible with the Ku-band antennas (Lilly, 1990; Sachdev et al., 1990). When used in the AOR, the VII series satellite is inverted north for south (Lilly, 1990), minor adjustments then being needed only to optimize the antenna pat- terns for this region. The lifetime of these satellites ranges from 10 to 15 years depending on the launch vehicle.

Recent figures from the INTELSAT Web site give the capacity for the INTELSAT VII as 18,000 two-way telephone circuits and three TV channels; up to 90,000 two-way telephone circuits can be achieved with the use of "digital circuit mul- tiplication."

The INTELSAT VII/A has a capacity of 22,500 two-way telephone circuits and three TV channels; up to 112,500 two-way tele- phone circuits can be achieved with the use of digital circuit multipli- cation. As of May 1999, four satellites were in service over the AOR, one in the IOR, and two in the POR.



Designation: Intelsat	I	II	III	IV	IV A	V	V A/V B	VI
Year of first launch	1965	1966	1968	1971	1975	1980	1984/85	1986/87
Prime contractor	Hughes	Hughes	TRW	Hughes	Hughes	Ford Aerospace	Ford Aerospace	Hughes
Width (m)	0.7	1.4	1.4	2.4	2.4	2.0	2.0	3.6
Height (m)	0.6	0.7	1.0	5.3	6.8	6.4	6.4	6.4
Launch vehicles		Thor Delta		Atlas-Centaur		Atlas-Centaur and Ariane	Atlas-Centaur and Ariane	STS and Ariane
Spacecraft mass in transfer orbit (kg)	68	182	293	1385	1489	1946	2140	12,100/3720
Communications payload mass (kg)	13	36	56	185	190	235	280	800
End-of-life (EOL) power of equinox (W)	40	75	134	480	800	1270	1270	2200
Design lifetime (years)	1.5	3	5	7	7	7	7	10
Capacity (number of voice channels)	480	480	2400	8000	12,000	25,000	30,000	80,000
Bandwidth (MHz)	50	130	300	500	800	2137	2480	3520

Figure 5.1 INTELSAT Series

The INTELSAT VIII-VII/A series of satellites was launched over the period February 1997 to June 1998. Satellites in this series have similar capacity as the VII/A series, and the lifetime is 14 to 17 years.

It is standard practice to have a spare satellite in orbit on high- reliability routes (which can carry preemptible traffic) and to have a ground spare in case of launch failure.

Thus the cost for large international schemes can be high; for example, series IX, described later, represents a total investment of approximately $1 billion.

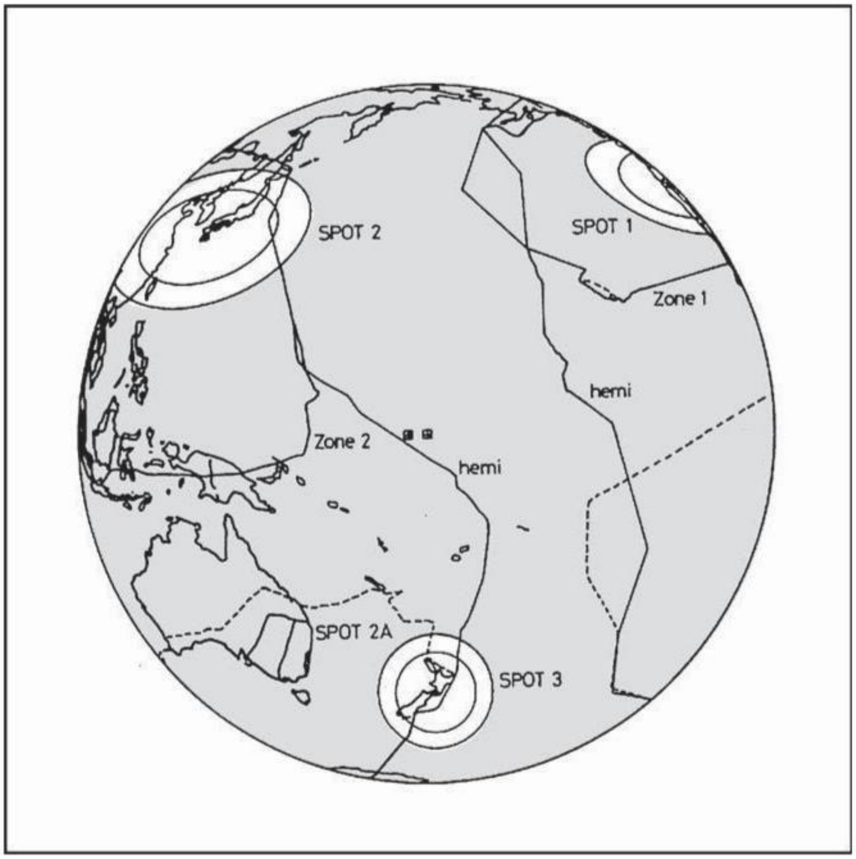


Figure 5.2 Region of glob

INSAT:

INSAT or the ***Indian National Satellite System*** is a series of multipurpose geo-stationary satellites launched by ISRO to satisfy the telecommunications, broadcasting, meteorology, and search and rescue operations.

Commissioned in 1983, INSAT is the largest domestic communication system in the Asia Pacific Region. It is a joint venture of the Department of Space, Department of Telecommunications, India Meteorological Department, All India Radio and Doordarshan. The overall coordination and management of INSAT system rests with the Secretary-level INSAT Coordination Committee.

INSAT satellites provide transponders in various bands (C, S, Extended C and K_u) to serve the television and communication needs of India. Some of the satellites also have the Very High Resolution Radiometer (VHRR), CCD cameras for metrological imaging.

The satellites also incorporate transponder(s) for receiving distress alert signals for search and rescue missions in the South Asian and Indian Ocean Region, as ISRO is a member of the Cospas-Sarsat programme.

INSAT System:.

The Indian National Satellite (INSAT) System Was Commissioned With The Launch Of INSAT-1B In August 1983 (INSAT-1A, The First Satellite Was Launched In April 1982 But Could Not Fulfil The Mission).

INSAT System Ushered In A Revolution In India's Television And Radio Broadcasting, Telecommunications And Meteorological Sectors. It Enabled The Rapid Expansion Of TV And Modern Telecommunication Facilities To Even The Remote Areas And Off-Shore Islands.

Satellites In Service:

Of The 24 Satellites Launched In The Course Of The INSAT Program, 10 Are Still In Operation.INSAT-2E

It Is The Last Of The Five Satellites In INSAT-2 Series{Prateek }. It Carries Seventeen C-Band And Lower Extended C-Band Transponders Providing Zonal And Global Coverage With An Effective Isotropic Radiated Power (EIRP) Of 36 Dbw.

It Also Carries A Very High Resolution Radiometer (VHRR) With Imaging Capacity In The Visible (0.55-0.75 µm), Thermal Infrared (10.5-12.5 µm) And Water Vapour (5.7-7.1 µm) Channels And Provides 2x2 Km, 8x8 Km And 8x8 Km Ground Resolution Respectively.

INSAT-3A

The Multipurpose Satellite, INSAT-3A, Was Launched By Ariane In April 2003. It Is Located At 93.5 Degree East Longitude. The Payloads On INSAT-3A Are As Follows:

12 Normal C-Band Transponders (9 Channels Provide Expanded Coverage From Middle East To South East Asia With An EIRP Of 38 Dbw, 3 Channels Provide India Coverage With An EIRP Of 36 Dbw And 6 Extended C-Band Transponders Provide India Coverage With An EIRP Of 36 Dbw).

A CCD Camera Provides 1x1 Km Ground Resolution, In The Visible (0.63 - μm), Near Infrared (0.77-0.86 μm) And Shortwave Infrared (1.55-1.70 μm) Bands.

INSAT-3D

Launched In July 2013, INSAT-3D Is Positioned At 82 Degree East Longitude. INSAT-3D Payloads Include Imager, Sounder, Data Relay Transponder And Search & Rescue Transponder. All The Transponders Provide Coverage Over Large Part Of The Indian Ocean Region Covering India, Bangladesh, Bhutan,Maldives, Nepal, Seychelles, Sri Lanka And Tanzania For Rendering Distress Alert Services

INSAT-3E

Launched In September 2003, INSAT-3E Is Positioned At 55 Degree East Longitude And Carries 24 Normal C-Band Transponders Provide An Edge Of Coverage EIRP Of 37 Dbw Over India And 12 Extended C-Band Transponders Provide An Edge Of Coverage EIRP Of 38 Dbw Over India.

KALPANA-1

KALPANA-1 Is An Exclusive Meteorological Satellite Launched By PSLV In September 2002. It Carries Very High Resolution Radiometer And DRT Payloads To Provide Meteorological Services. It Is Located At 74 Degree East Longitude. Its First Name Was METSAT. It Was Later Renamed As KALPANA-1 To Commemorate Kalpana Chawla.

Edusat

Configured For Audio-Visual Medium Employing Digital Interactive Classroom Lessons And Multimedia Content, EDUSAT Was Launched By GSLV In September 2004. Its Transponders And Their Ground Coverage Are Specially Configured To Cater To The Educational Requirements.

GSAT-2

Launched By The Second Flight Of GSLV In May 2003, GSAT-2 Is Located At 48 Degree East Longitude And Carries Four Normal C-Band Transponders To Provide 36 Dbw EIRP With India Coverage, Two K_u Band Transponders With 42 Dbw EIRP Over India And An MSS Payload Similar To Those On INSAT-3B And INSAT-3C.

INSAT-4 Series:

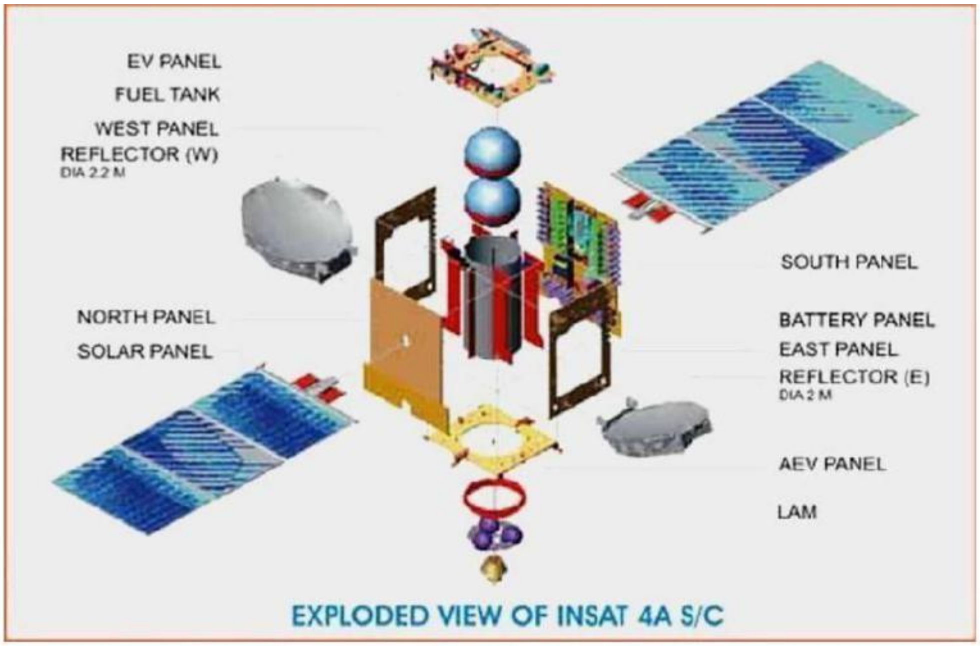


Figure 5.3 INSAT 4A

INSAT-4A is positioned at 83 degree East longitude along with INSAT-2E and INSAT-3B. It carries 12 K_u band 36 MHz bandwidth transponders employing 140 W TWTAs to provide an EIRP of 52 dBW at the edge of coverage polygon with footprint covering Indian main land and 12 C-band 36 MHz bandwidth transponders provide an EIRP of 39 dBW at the edge of coverage with expanded radiation patterns encompassing Indian geographical boundary, area beyond India in southeast and northwest regions.[8] Tata Sky, a joint venture between the TATA Group and STAR uses INSAT-4A for distributing their DTH service.

INSAT-4A

INSAT-4B

Glitch In INSAT 4B

China-Stuxnet Connection

INSAT-4CR

GSAT-8 / INSAT-4G

GSAT-12 /GSAT-10

VSAT:

VSAT stands for *very small aperture terminal* system. This is the dis-tinguishing feature of a VSAT system, the earth-station antennas being typically less than 2.4 m in diameter (Rana et al., 1990). The trend is toward even smaller dishes, not more than 1.5 m in diameter (Hughes et al., 1993).

In this sense, the small TVRO terminals for direct broadcast satellites could be labeled as VSATs, but the appellation is usually reserved for private networks, mostly providing two-way communications facilities.

Typical user groups include bank- ing and financial institutions, airline and hotel booking agencies, and large retail stores with geographically dispersed outlets.

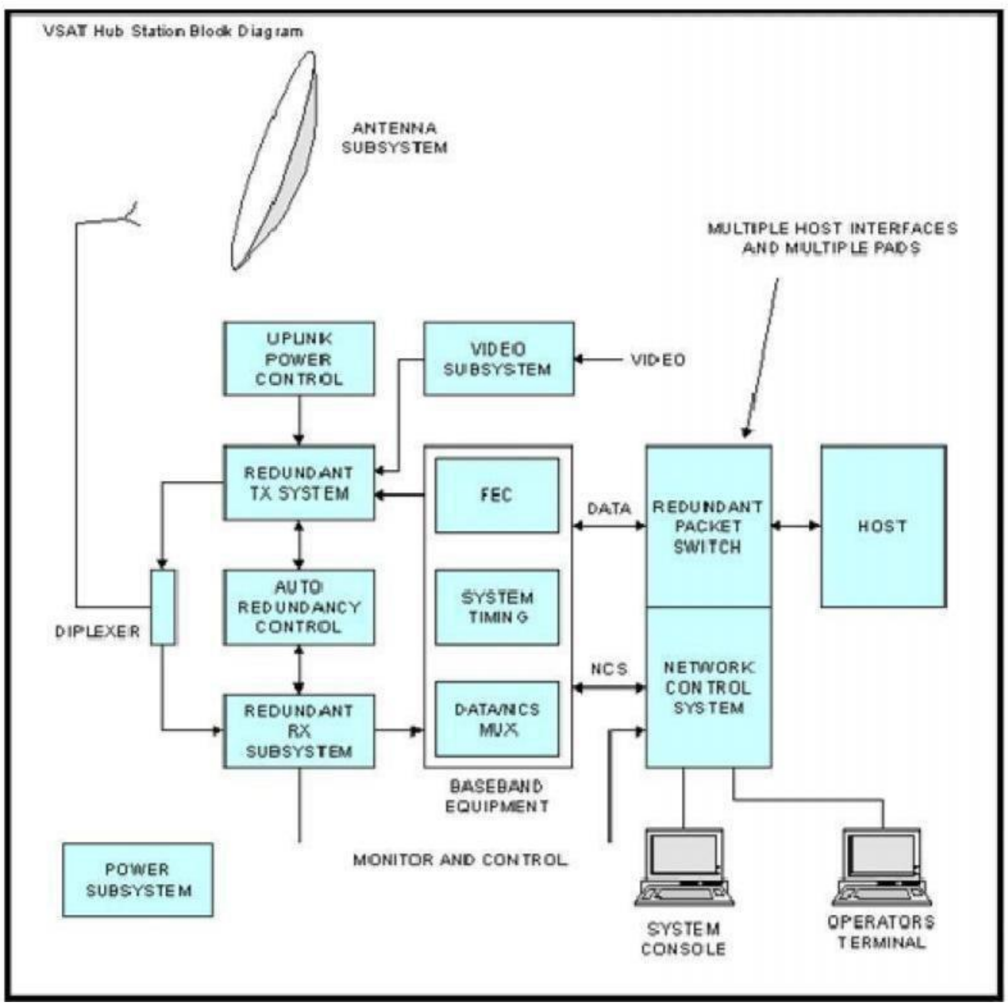


Figure 5.4 VSAT Block Diagrams

VSAT network :

The basic structure of a VSAT network consists of a hub station which provides a broadcast facility to all the VSATs in the network and the VSATs themselves which access the satellite in some form of multiple- access mode.

The hub station is operated by the service provider, and it may be shared among a number of users, but of course, each user organ- ization has exclusive access to its own VSAT network.

Time division mul- tiplex is the normal downlink mode of transmission from hub to the VSATs, and the transmission can be broadcast for reception by all the VSATs in a network, or address coding can be used to direct messages to selected VSATs.

A form of *demand assigned multiple access* (DAMA) is employed in some systems in which channel capacity is assigned in response to the fluctuating demands of the VSATs in the network.

Most VSAT systems operate in the Ku band, although there are some C-band systems in existence (Rana et al., 1990).

Applications:

- ✓ Supermarket shops (tills, ATM machines, stock sale updates and stock ordering).
- ✓ Chemist shops - Shoppers Drug Mart - Pharmaprix. Broadband direct to the home. e.g. Downloading MP3 audio to audio players.
- ✓ Broadband direct small business, office etc, sharing local use with many PCs.
- ✓ Internet access from on board ship Cruise ships with internet cafes, commercial shipping communications.

Mobile satellite services:

GSM:

Services and Architecture:

If your work involves (or is likely to involve) some form of wireless public communications, you are likely to encounter the GSM standards. Initially developed to support a standardized approach to digital cellular communications in Europe, the "Global System for Mobile Communications" (GSM) protocols are rapidly being adopted to the next generation of wireless telecommunications systems.

In the US, its main competition appears to be the cellular TDMA systems based on the IS-54 standards. Since the GSM systems consist of a wide range of components, standards, and protocols.

The GSM and its companion standard DCS1800 (for the UK, where the 900 MHz frequencies are not available for GSM) have been developed over the last decade to allow cellular communications systems to move beyond the limitations posed by the older analog systems.

Analog system capacities are being stressed with more users that can be effectively supported by the available frequency allocations. Compatibility between types of systems had been limited, if non-existent.

By using digital encoding techniques, more users can share the same frequencies than had been available in the analog systems. As compared to the digital cellular systems in the US (CDMA [IS-95] and TDMA [IS-54]), the GSM market has had impressive success. Estimates of the numbers of telephones run from 7.5 million GSM phones to .5 million IS54 phones to .3 million for IS95.

GSM has gained in acceptance from its initial beginnings in Europe to other parts of the world including Australia, New Zealand, countries in the Middle East and the far east. Beyond its use in cellular frequencies (900 MHz for GSM, 1800 MHz for DCS1800), portions of the GSM signaling protocols are finding their way into the newly developing PCS and LEO Satellite communications systems.

While the frequencies and link characteristics of these systems differ from the standard GSM air interface, all of these systems must deal with users roaming from one cell (or satellite beam) to another, and bridge services to public communication networks including the Public Switched Telephone Network (PSTN), and public data networks (PDN).

The GSM architecture includes several subsystems:

The Mobile Station (MS) -- These digital telephones include vehicle, portable and hand-held terminals. A device called the Subscriber Identity Module (SIM) that is basically a smart-card provides custom information about users such as the services they've subscribed to and their identification in the network

The Base Station Sub-System (BSS) -- The BSS is the collection of devices that support the switching networks radio interface. Major components of the BSS include the Base Transceiver Station (BTS) that consists of the radio modems and antenna equipment.

In OSI terms, the BTS provides the physical interface to the MS where the BSC is responsible for the link layer services to the MS. Logically the transcoding equipment is in the BTS, however, an additional component.

The Network and Switching Sub-System (NSS) -- The NSS provides the switching between the GSM subsystem and external networks along with the databases usedforadditionalsubscriberandmobilitymanagement.

Major components in the NSS include the Mobile Services Switching Center (MSC), Home and Visiting Location Registers (HLR, VLR). The HLR and VLR databases are interconnected through the telecomm standard Signaling System 7 (SS7) control network.

The Operation Sub-System (OSS) -- The OSS provides the support functions responsible for the management of network maintenance and services. Components of the OSS are responsible for network operation and maintenance, mobile equipment management, and subscription management and charging.

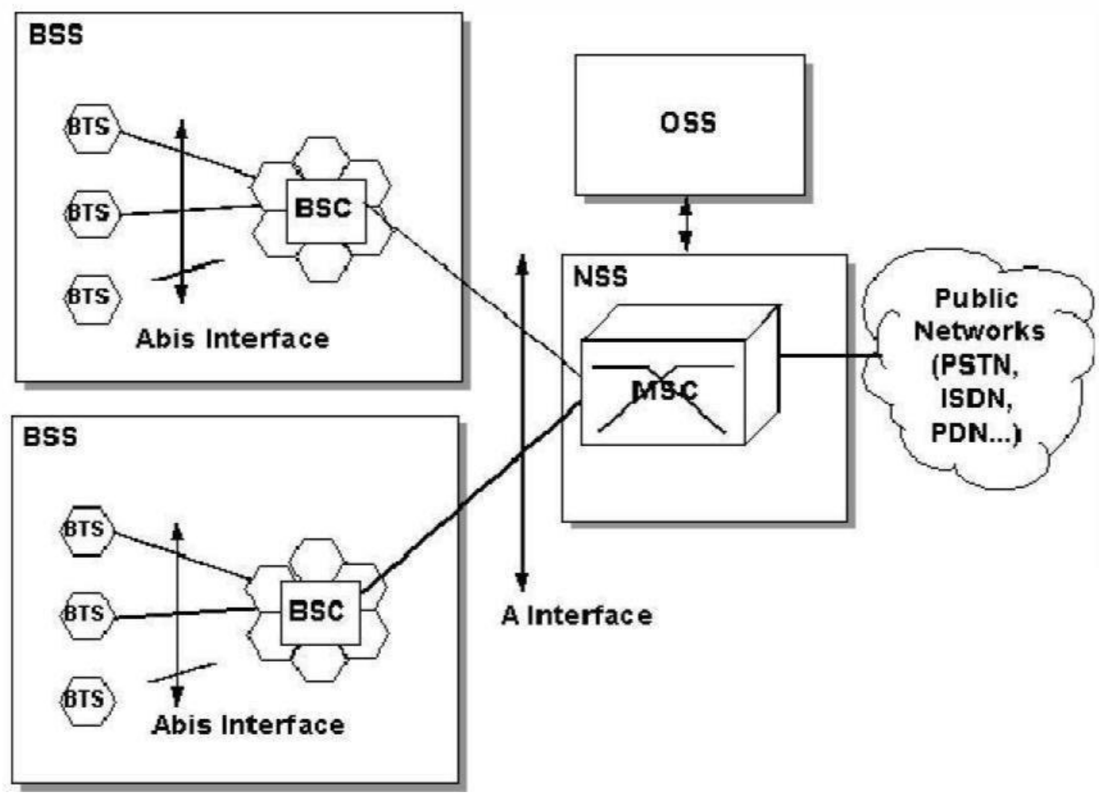


Figure 5.5 GSM Block Diagrams

Several channels are used in the air interface:

- ✓ **FCCH** - the frequency correction channel - provides frequency synchronization information in a burst
- ✓ **SCH** - Synchronization Channel - shortly following the FCCH burst (8 bits later), provides a reference to all slots on a given frequency
- ✓ **PAGCH** - Paging and Access Grant Channel used for the transmission of paging information requesting the setup of a call to a MS.
- ✓ **RACH** - Random Access Channel - an inbound channel used by the MS to request connections from the ground network. Since this is used for the first access attempt by users of the network, a random access scheme is used to aid in avoiding collisions.
- ✓ **CBCH -** Cell Broadcast Channel - used for infrequent transmission of broadcasts by the ground network.
- ✓ **BCCH** - Broadcast Control Channel - provides access status information to the MS. The information provided on this channel is used by the MS to determine whether or not to request a transition to a new cell

- ✓ **FACCH -** Fast Associated Control Channel for the control of handovers
- ✓ **TCH/F** - Traffic Channel, Full Rate for speech at 13 kbps or data at 12, 6, or 3.6 kbps
- ✓ **TCH/H** - Traffic Channel, Half Rate for speech at 7 kbps, or data at 6 or 3.6 kbps

Mobility Management:

One of the major features used in all classes of GSM networks (cellular, PCS and Satellite) is the ability to support roaming users. Through the control signaling network, the MSCs interact to locate and connect to users throughout the network.

"Location Registers" are included in the MSC databases to assist in the role of determining how, and whether connections are to be made to roaming users. Each user of a GSM MS is assigned a Home Location Register (HLR) that is used to contain the user's location and subscribed services.

Difficulties facing the operators can include;

a. Remote/Rural Areas. To service remote areas, it is often economically unfeasible to provide backhaul facilities (BTS to BSC) via terrestrial lines (fiber/microwave).

b. Time to deploy. Terrestrial build-outs can take years to plan and implement.
c. Areas of 'minor' interest. These can include small isolated centers such as tourist resorts, islands, mines, oil exploration sites, hydro-electric facilities.
d. Temporary Coverage. Special events, even in urban areas, can overload the existing infrastructure.

GSM service security:

GSM was designed with a moderate level of service security. GSM uses several cryptographic algorithms for security. The A5/1, A5/2, and A5/3 stream ciphers are used for ensuring over-the-air voice privacy.

GSM uses General Packet Radio Service (GPRS) for data transmissions like browsing the web. The most commonly deployed GPRS ciphers were publicly broken in 2011The researchers revealed flaws in the commonly used GEA/1.

Global Positioning System (GPS) :

The Global Positioning System (GPS) is a satellite based navigation system that can be used to locate positions anywhere on earth. Designed and operated by the U.S. Department of Defense, it consists of satellites, control and monitor stations, and receivers. GPS receivers take information transmitted from the satellites and uses triangulation to calculate a user's exact location. GPS is used on incidents in a variety of ways, such as:

- To determine position locations; for example, you need to radio a helicopter pilot the coordinates of your position location so the pilot can pick you up.
- To navigate from one location to another; for example, you need to travel from a lookout to the fire perimeter.
- To create digitized maps; for example, you are assigned to plot the fire perimeter and hot spots.
- To determine distance between two points or how far you are from another location.

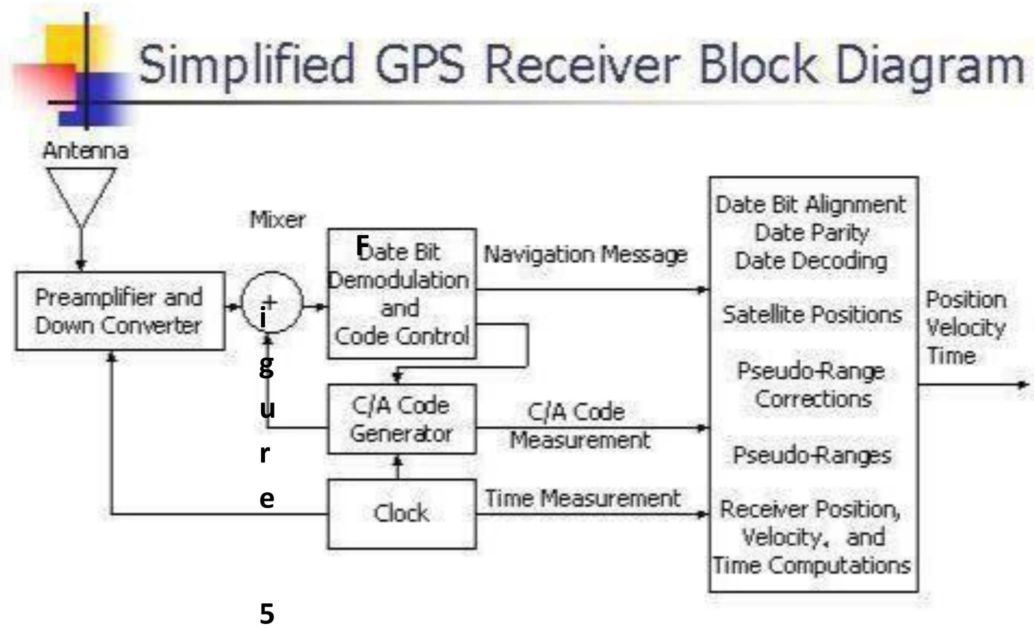


Figure 5.6 GPS Block Diagrams

The purpose of this chapter is to give a general overview of the Global Positioning System, not to teach proficiency in the use of a GPS receiver. To become proficient with a specific GPS receiver, study the owner's manual and practice using the receiver.

The chapter starts with a general introduction on how the global positioning system works. Then it discusses some basics on using a GPS receiver.

Three Segments of GPS:

Space Segment — Satellites orbiting the earth

The space segment consists of 29 satellites circling the earth every 12 hours at 12,000 miles in altitude. This high altitude allows the signals to cover a greater area. The satellites are arranged in their orbits so a GPS receiver on earth can receive a signal from at least four satellites at any given time. Each satellite contains several atomic clocks.

Control Segment — The control and monitoring stations

The control segment tracks the satellites and then provides them with corrected orbital and time information. The control segment consists of five unmanned monitor stations and one Master Control Station. The five unmanned stations monitor GPS satellite signals and then send that information to the Master Control Station where anomalies are corrected and sent back to the GPS satellites through ground antennas.

User Segment — The GPS receivers owned by civilians and military

The user segment consists of the users and their GPS receivers. The number of simultaneous users is limitless.

How GPS Determines a Position:

The GPS receiver uses the following information to determine a position.

- ✓ Precise location of satellites

When a GPS receiver is first turned on, it downloads orbit information from all the satellites called an almanac. This process, the first time, can take as long as 12 minutes; but once this information is downloaded, it is stored in the receiver's memory for future use.

- Distance from each satellite

The GPS receiver calculates the distance from each satellite to the receiver by using the distance formula: distance = velocity x time. The receiver already knows the velocity, which is the speed of a radio wave or 186,000 miles per second (the speed of light).

- Triangulation to determine position

The receiver determines position by using triangulation. When it receives signals from at least three satellites the receiver should be able to calculate its approximate position (a 2D position). The receiver needs at least four or more satellites to calculate a more accurate 3D position.

Using a GPS Receiver :

There are several different models and types of GPS receivers. Refer to the owner's manual for your GPS Receiver and practice using it to become proficient

- When working on an incident with a GPS receiver it is important to:
- Always have a compass and a map.
- Have a GPS download cable.
- Have extra batteries.
- Know memory capacity of the GPS receiver to prevent loss of data, decrease in accuracy of data,or other problems.
- Use an external antennae whenever possible, especially under tree canopy, in canyons, or while flying or driving.
- Set up GPS receiver according to incident or agency standard regulation; coordinate system.
- Take notes that describe what you are saving in the receiver.

INMARSAT:

Inmarsat-Indian Maritime SATellite is still the sole IMO-mandated provider of satellite communications for the GMDSS.

Availability for GMDSS is a minimum of 99.9%

Inmarsat has constantly and consistently exceeded this figure & Independently audited by IMSO and reported on to IMO.

Now Inmarsat commercial services use the same satellites and network &Inmarsat A closes at midnight on 31 December 2007 Agreed by IMO – MSC/Circ.1076. Successful closure programme almost concluded Overseen throughout by IMSO.

Figure 5.7 INMARSAT Satellite Service

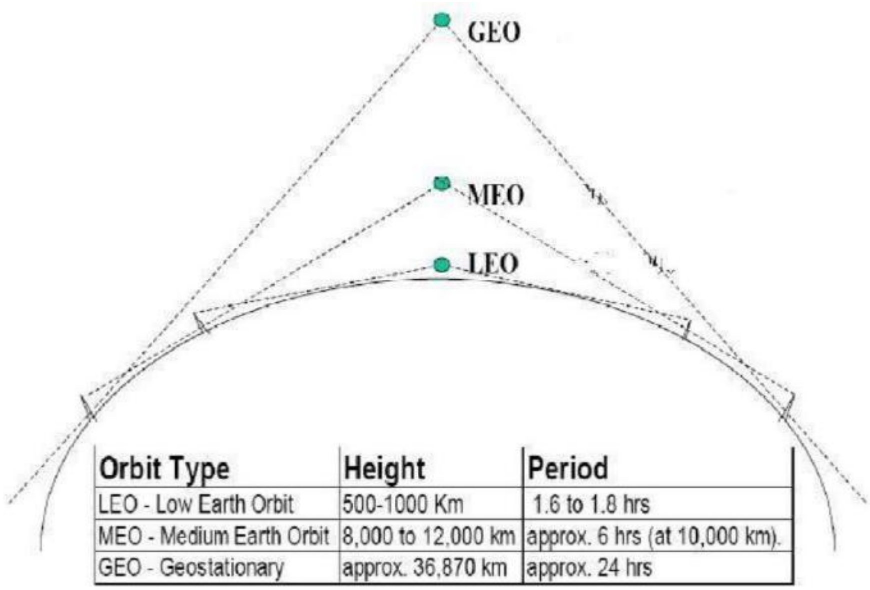
GMDSS services continue to be provided by:

Inmarsat B, Inmarsat C/mini-C and Inmarsat Fleet F77
Potential for GMDSS on FleetBroadband being assessed

- The IMO Criteria for the Provision of Mobile Satellite Communications Systems in the Global Maritime Distress and Safety System (GMDSS)
- Amendments were proposed; potentially to make it simpler for other satellite systems to be approved
- The original requirements remain and were approved by MSC 83
  - No dilution of standards
- Minor amendments only; replacement Resolution expected to be approved by the IMO 25th Assembly
- Inmarsat remains the sole, approved satcom provider for the GMDSS

LEO: Low Earth Orbit satellites have a small area of coverage. They are positioned in an orbit approximately 3000km from the surface of the earth

- They complete one orbit every 90 minutes
- The large majority of satellites are in low earth orbit
- The Iridium system utilizes LEO satellites (780km high)
- The satellite in LEO orbit is visible to a point on the earth for avery short time



Orbit Type	Height	Period
LEO - Low Earth Orbit	500-1000 Km	1.6 to 1.8 hrs
MEO - Medium Earth Orbit	8,000 to 12,000 km	approx. 6 hrs (at 10,000 km).
GEO - Geostationary	approx. 36,870 km	approx. 24 hrs

Figure 5.8 LEO, MEO & GEO range

MEO: *Medium Earth Orbit* satellites have orbital altitudes between 3,000 and 30,000 km.

- They are commonly used used in navigation systems such as GPS

GEO: *Geosynchronous (Geostationary) Earth Orbit* satellites are positioned over the equator. The orbital altitude is around 30,000-40,000 km

- There is only one geostationary orbit possible around the earth
  - Lying on the earth's equatorial plane.
  - The satellite orbiting at the same speed as the rotational speed of the earth on its axis.
  - They complete one orbit every 24 hours. This causes the satellite to appear stationary with respect to a point on the earth, allowing one satellite to provide continual coverage to a given area on the earth's surface
  - One GEO satellite can cover approximately 1/3 of the world's surface

They are commonly used in communication systems

- Advantages:
  - Simple ground station tracking.
  - Nearly constant range
  - Very small frequency shift
- Disadvantages:

- Transmission delay of the order of 250 msec.
- Large free space loss.
- No polar coverage

- Satellite orbits in terms of the orbital height:
- According to distance from earth:
  - Geosynchronous Earth Orbit (GEO) ,
  - Medium Earth Orbit (MEO),
  - Low Earth Orbit (LEO)

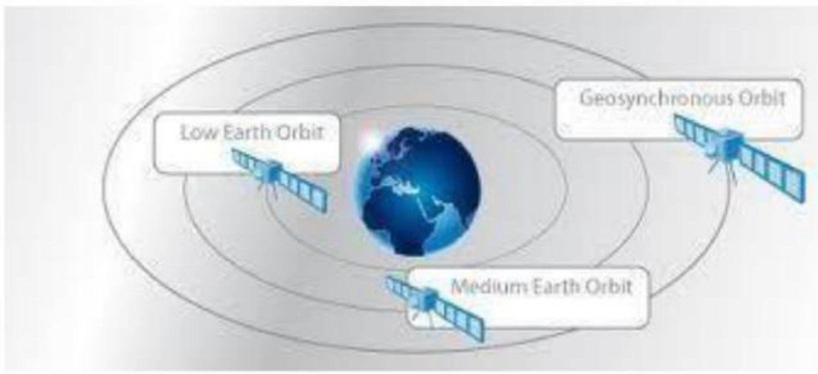


Figure 5.9 LEO, MEO & GEO Orbits

LEO / MEO / GEO / HEO (cont.)

	Name	Number	Panel	No./Panel	altitude	deg.
LEO	STARSYS	24	6	4	1300km	60
	ORBCOMM	24	4	6	785km	45
	GLOBALSTAR	48	8	6	1400km	52
	IRIDIUM	66	6	11	765km	86
MEO	Name	Number	Panel	No./Panel	altitude	deg.
	INMARSAT P	10	2	5	10300km	45
	ODYSEEY	12	3	4	10370km	55
	GPS	24	6	4	20200km	55
	GLONASS	24	3	8	19132km	64.8
HEO	Name	Number	Panel	No./Panel	altitude	deg.
	ELLIPSO	24	4	6	A:7800km P:520km	63.4
	MOLNIYA	4	1	4	A:39863km P:504km	63.4
	ARCHIMEDES	4	4	1	A:39447km P:926km	63.4

9

Figure 5.10 Diff b/w LEO, MEO & GEO Orbits

GEO: 35,786 km above the earth, MEO: 8,000-20,000 km above the earth & LEO: 500-2,000 km above the earth.

Satellite

Navigational System:

Benefits:

- Enhanced Safety
- Increased Capacity
- Reduced Delays

Advantage:

- Increased Flight Efficiencies
- Increased Schedule Predictability
- Environmentally Beneficial Procedures

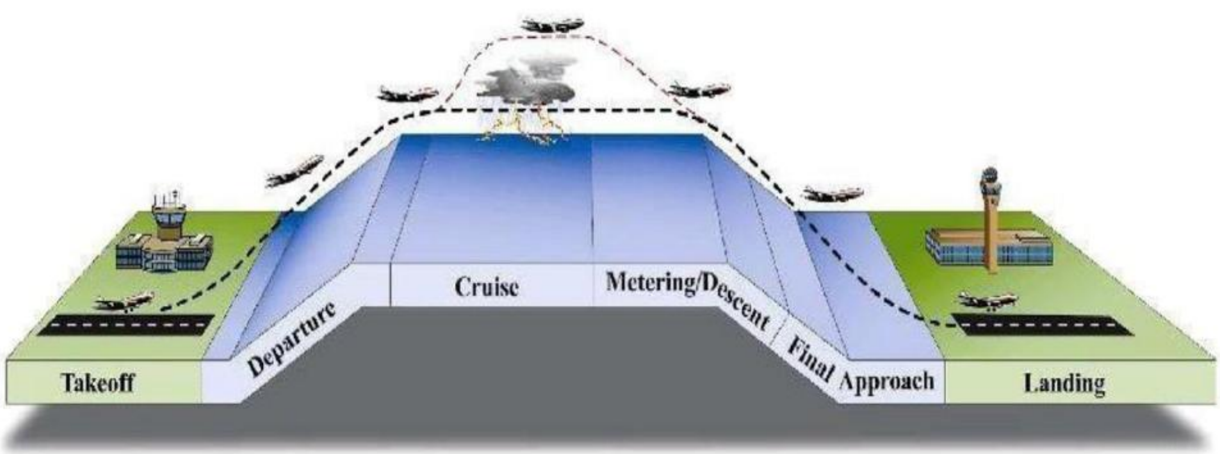


Figure 5.11 LEO, MEO & GEO Orbits

- Using ICAO GNSS Implementation Strategy and ICAO Standards and Recommended Practices
- GPS Aviation Use Approved for Over a Decade
  - Aircraft Based Augmentation Systems (ABAS) – (e.g. RAIM)

- Space Based Augmentation System (SBAS) since 2003
  - Wide Area Augmentation System (WAAS) augmenting GPS
- Development of GNSS Ground Based Augmentation System (GBAS) Continues
  - Local Area Augmentation System (LAAS)
- GNSS is Cornerstone for National Airspace System

Direct Broadcast satellites (DBS):

Satellites provide *broadcast* transmissions in the fullest sense of the word, because antenna footprints can be made to cover large areas of the earth.

The idea of using satellites to provide direct transmissions into the home has been around for many years, and the services pro- vided are known generally as *direct broadcast satellite* (DBS) services.

Broadcast services include audio, television, and Internet services.

Power Rating and Number of Transponders:

From Table 1.4 it will be seen that satellites primarily intended for DBS have a higher [EIRP] than for the other categories, being in the range 51 to 60 dBW. At a *Regional Administrative Radio Council* (RARC) meeting in 1983, the value established for DBS was 57 dBW (Mead,2000). Transponders are rated by the power output of their high-power amplifiers.

Typically, a satellite may carry 32 transponders. If all 32 are in use, each will operate at the lower power rating of 120 W.

The available bandwidth (uplink and downlink) is seen to be 500 MHz. A total number of 32 transponder channels, each of bandwidth 24 MHz, can be accommodated.

The bandwidth is sometimes specified as 27 MHz, but this includes a 3-MHz guardband allowance. Therefore, when calculating bit-rate capacity, the 24 MHz value is used.

The total of 32 transponders requires the use of both *right- hand circular polarization* (RHCP) and *left-hand circular polarization* (LHCP) in order to permit frequency reuse, and guard bands are inserted between channels of a given polarization.

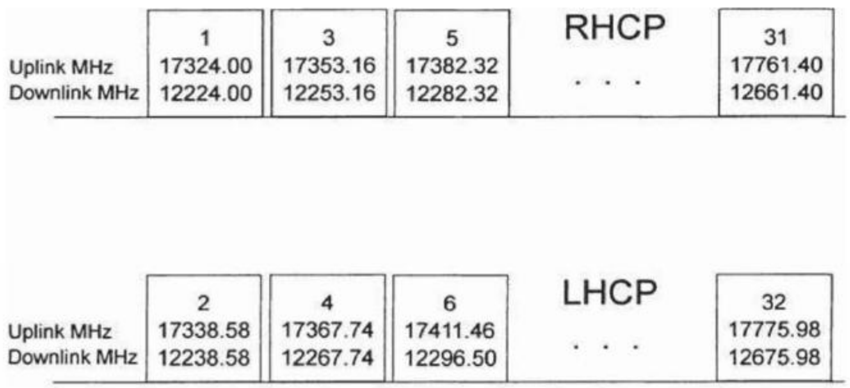


Figure 5.12 DBS Service

Bit Rates for Digital Television:

The bit rate for digital television depends very much on the picture format. One way of estimating the uncompressed bit rate is to multiply the number of pixels in a frame by the number of frames per second, and multiply this by the number of bits used to encode each pixel.

MPEG Compression Standards:

MPEG is a group within the *International Standards Organization and the International Electrochemical Commission* (ISO/IEC) that undertook the job of defining standards for the transmission and storage of moving pictures and sound.

The MPEG standards currently available are MPEG-1, MPEG-2, MPEG-4, and MPEG-7.

Direct to home Broadcast (DTH):

DTH stands for Direct-To-Home television. DTH is defined as the reception of satellite programmes with a personal dish in an individual home.

- ✓ DTH Broadcasting to home TV receivers take place in the ku band(12 GHz). This service is known as Direct To Home service.
- ✓ DTH services were first proposed in India in 1996.
- ✓ Finally in 2000, DTH was allowed.
- ✓ The new policy requires all operators to set up earth stations in India within 12 months of getting a license. DTH licenses in India will cost $2.14 million and will be valid for 10 years.

Working principal of DTH is the satellite communication. Broadcaster modulates the received signal and transmit it to the satellite in KU Band and from satellite one can receive signal by dish and set top box.

DTH Block Diagram:

- ✓ A DTH network consists of a broadcasting centre, satellites, encoders, multiplexers, modulators and DTH receivers
- ✓ The encoder converts the audio, video and data signals into the digital format and the multiplexer mixes these signals.

It is used to provide the DTH service in high populated area A Multi Switch is basically a box that contains signal splitters and A/B switches. A outputs of group of DTH LNBs are connected to the A and B inputs of the Multi Switch.

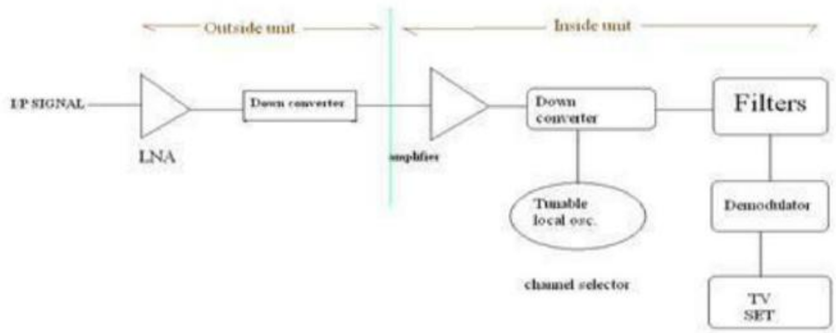


Figure 5.13 DTH Service

Advantage:

- ✓ DTH also offers digital quality signals which do not degrade the picture or sound quality.
- ✓ It also offers interactive channels and program guides with customers having the choice to block out programming which they consider undesirable

- ✓ One of the great advantages of the cable industry has been the ability to provide local channels, but this handicap has been overcome by many DTH providers using other local channels or local feeds.

- ✓ The other advantage of DTH is the availability of satellite broadcast in rural and semi-urban areas where cable is difficult to install.

Digital audio broadcast (DAB):

DAB Project is an industry-led consortium of over 300 companies

- ✓ The DAB Project was launched on 10th September, 1993
- ✓ In 1995 it was basically finished and became operational
- ✓ There are several sub-standards of the DAB standard
    - DAB-S (Satellite) – using QPSK – 40 Mb/s
    - DAB-T (Terrestrial) – using QAM – 50 Mb/s
    - DAB-C (Cable) – using OFDM – 24 Mb/s
- ✓ These three sub-standards basically differ only in the specifications to the physical representation, modulation, transmission and reception of the signal.

- ✓ The DAB stream consists of a series of fixed length packets which make up a Transport Stream (TS). The packets support 'streams' or 'data sections'.

- ✓ Streams carry higher layer packets derived from an MPEG stream & Data sections are blocks of data carrying signaling and control data.

- ✓ DAB is actually a support mechanism for MPEG.& One MPEG stream needing higher instantaneous data can ‘steal’ capacity from another with spare capacity.

Worldspace services:

WorldSpace (Nasdaq: WRSP) is the world's only global media and entertainment company positioned to offer a satellite radio experience to consumers in more than 130 countries with five billion people, driving 300 million cars. WorldSpace delivers the latest tunes, trends and information from around the world and around the corner.

WorldSpace subscribers benefit from a unique combination of local programming, original WorldSpace content and content from leading brands around the globe, including the BBC, CNN, Virgin Radio, NDTV and RFI.
WorldSpace's satellites cover two-thirds of the globe with six beams.

Each beam is capable of delivering up to 80 channels of high quality digital audio and multimedia programming directly to WorldSpace Satellite Radios anytime and virtually anywhere in its coverage area. WorldSpace is a pioneer of satellite-based digital radio services (DARS) and was instrumental in the development of the technology infrastructure used today by XM Satellite Radio. For more information, visit Business Television (BTV) - Adaptations for Education:

Business television (BTV) is the production and distribution, via satellite, of video programs for closed user group audiences. It often has two-way audio interaction component made through a simple telephone line. It is being used by many industries including brokerage firms, pizza houses, car dealers and delivery services.

BTV is an increasingly popular method of information delivery for corporations and institutions. Private networks, account for about 70 percent of all BTV networks. It is estimated that by the mid-1990s BTV has the potential to grow to a $1.6 billion market in North America with more and more Fortune 1,000 companies getting involved.

Institution updates, news, training, meetings and other events can be broadcast live to multiple locations. The expertise of the best instructors can be delivered to thousands of people without requiring trainers to go to the site. Information can be disseminated to all employees at once, not just a few at a time. Delivery to the workplace at low cost provides the access to training that has been denied lower level employees. It may be the key to re-training America's work force.

Television has been used to deliver training and information within businesses for more than 40 years. Its recent growth began with the introduction of the video cassette in the early 1970s. Even though most programming is produced for video cassette distribution, business is using BTV to provide efficient delivery of specialized programs via satellite.

The advent of smaller receiving stations - called very small aperture terminals (VSATs) has made private communication networks much more economical to operate. BTV has a number of tangible benefits, such as reducing travel, immediate delivery of time-critical messages, and eliminating cassette duplication and distribution hassles.

The programming on BTV networks is extremely cost-effective compared to seminar fees and downtime for travel. It is an excellent way to get solid and current information very fast. Some people prefer to attend seminars and conferences where they can read, see, hear and ask questions in person. BTV provides yet another piece of the education menu and is another way to provide professional development.

A key advantage is that its format allows viewers to interact with presenters by telephone, enabling viewers to become a part of the program. The satellite effectively places people in the same room, so that sales personnel in the field can learn about new products at the same time.

Speed of transmission may well be the competitive edge which some firms need as they introduce new products and services. BTV enables employees in many locations to focus on common problems or issues that might develop into crises without quick communication and resolution.

BTV networks transmit information every business day on a broad range of topics, and provide instructional courses on various products, market trends, selling and motivation. Networks give subscribers the tools to apply the information they have to real world situations.

GRAMSAT:

ISRO has come up with the concept of dedicated GRAMSAT satellites, keeping in mind the urgent need to eradicate illiteracy in the rural belt which is necessary for the all round development of the nation.

This Gramsat satellite is carrying six to eight high powered C-band transponders, which together with video compression techniques can disseminate regional and cultural specific audio-visual programmes of relevance in each of the regional languages through rebroadcast mode on an ordinary TV set.

The high power in C-band has enabled even remote area viewers outside the reach of the TV transmitters to receive programmers of their choice in a direct reception mode with a simple .dish antenna.

The salient features of GRAMSAT projects are:

i. Its communications networks are at the state level connecting the state capital to districts, blocks and enabling a reach to villages.

ii. It is also providing computer connectivity data broadcasting, TV-broadcasting facilities having applications like e- governance, development information, teleconferencing, helping disaster management.

iii. Providing rural-education broadcasting.

However, the Gramsat projects have an appropriate combination of following activities.

(i) Interactive training at district and block levels employing suitable configuration

(ii) Broadcasting services for rural development

(iii) Computer interconnectivity and data exchange services

(iv) Tele-health and tele-medicine services.

Specialized services:

5.16.1 Satellite-email services:

The addition of Internet Access enables Astrium to act as an Internet Service Provider (ISP) capable of offering Inmarsat users a tailor-made Internet connection.

With Internet services added to our range of terrestrial networks, you will no longer need to subscribe to a third party for Internet access (available for Inmarsat A, B, M, mini-M, Fleet, GAN, Regional BGAN & SWIFT networks).

We treat Internet in the same way as the other terrestrial networks we provide, and thus offer unrestricted access to this service. There is no time-consuming log-on procedure, as users are not required to submit a user-ID or password.

Description of E-mail Service:

Astrium's E-Mail service allows Inmarsat users to send and receive e-mail directly through the Internet without accessing a public telephone network.

Features and Benefits

- ✓ No need to configure an e-mail client to access a Astrium e-mail account
- ✓ Service optimized for use with low bandwidth Inmarsat terminals
- ✓ Filter e-mail by previewing the Inbox and deleting any unwanted e-mails prior to downloading
- ✓ No surcharge or monthly subscription fees
- ✓ Service billed according to standard airtime prices for Inmarsat service used

5.16.2 Video Conferencing (medium resolution):

Video conferencing technology can be used to provide the same full, two-way interactivity of satellite broadcast at much lower cost. For Multi-Site meetings, video conferencing uses bridging systems to connect each site to the others.

It is possible to configure a video conference bridge to show all sites at the same time on a projection screen or monitor. Or, as is more typical, a bridge can show just the site from which a person is speaking or making a presentation.

The technology that makes interactive video conferencing possible, compresses video and audio signals, thus creating an image quality lower than that of satellite broadcasts.

5.16.3. Satellite Internet access:

Satellite Internet access is Internet access provided through communications satellites. Modern satellite Internet service is typically provided to users through geostationary satellites that can offer high data speeds, with newer satellites using Ka band to achieve downstream data speeds up to 50 Mbps.

Satellite Internet generally relies on three primary components: a satellite in geostationary orbit (sometimes referred to as a geosynchronous Earth orbit, or GEO), a number of ground stations known as gateways that relay Internet data to and from the satellite via radio waves (microwave), and a VSAT (very-small- aperture terminal) dish antenna with a transceiver, located at the subscriber's premises.

Other components of a satellite Internet system include a modem at the user end which links the user's network with the transceiver, and a centralized network operations center (NOC) for monitoring the entire system.