Satellite Subsystems

→ To support the satellites primary mission of communications like monitoring and controlling power, providing a controlled temperature environment, lifetime, antenna design etc.,

→ The major subsystems required on the satellite are given below.

① Attitude and Orbit Control System (AOCS)

② Telemetry, Tracking, Command & Monitoring Subsystem

③ Power Systems

④ Communication Subsystems

⑤ Satellite Antennas.

⊛ Attitude and Orbit Control System (AOCS)

→ This Subsystem Consists of rocket motors that are used to move the satellite back to the correct orbit when external forces cause it to drift off station and gas jets or inertial devices that control the attitude of the satellite.

→ The attitude and orbit of a satellite must be controlled so that the satellite's antennas point towards the earth and so that the user knows where in the sky to look for the satellite.

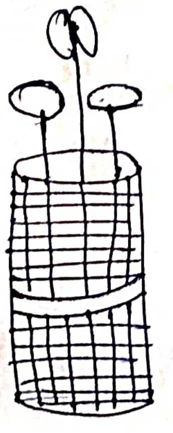
→ For Geo satellites, due to the movement of satellites away from its appointed position in the sky will cause a loss of signal.

→ There are several forces acting on an orbiting satellite that tend to change its attitude and orbit like gravitational fields of sun and moon, irregularities in earth's gravitational field & solar pressure from the sun etc. (orbital perturbations)

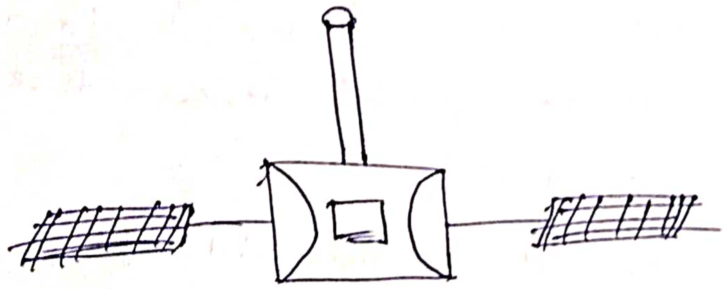
-> Solar pressure acting on satellites solar sails tend to cause rotation of the satellite body. The altitude control system must counter these rotations.

-> The presence of gravitational fields from sun and the moon cause the orbit of a GEO satellite to change with time. This gravitational pull on the satellite that tends to change the inclination of satellite's orbit must be controlled by orbital control system and be able to move the satellite back into the orbit.

- Attitude Control System:



(a) Spinner Satellite



(b) Three-axis stabilized Satellite.

→ There are two ways to make a satellite stable in orbit. The body of satellite can be rotated at a rate between 30 & 100rpm to provide stability of the spin axis and keeps it pointing in the same direction. Such satellites are known as "spinners". Alternatively, the satellite can be stabilized by one or more momentum wheels. The is called a "three-axis stabilized satellite". This momentum wheel is usually a solid metal disk driven by an electric motor to provide a rotational force on any of the three axes.

→ The spinner satellite consists of a cylindrical drum covered with solar cells that contains the power systems and rocket motors. Antennas are mounted on top of the drum and are driven by electric motor in the opposite direction to the rotation of satellite body to keep pointing towards the earth.

→ The satellite is spun up by operating small radial gas jets mounted on the drum. ~~A variety of liquid~~ A variant of hydrazine (N_2H_4) liquid mix is most commonly used for gas jets.

→ In a three-axis stabilized satellite, one pair of gas jets is needed for each axis to provide rotations in pitch, roll and yaw directions.

→ A set of reference Cartesian axes (X_R, Y_R, Z_R) with the satellite at origin is shown in figure 1.

→ Z_R is directed toward the center of earth

→ X_R is tangent to orbital plane.

→ Y_R is ~~directed~~ perpendicular to orbital plane.

→ Rotation about the X_R, Y_R, Z_R axes is defined as roll, pitch & Yaw.

→ The satellite must be stabilized with respect to reference axes to maintain accurate pointing of its antenna beams.

→ A second set of Cartesian axes X, Y, Z as shown in fig 1. define orientation of satellite.

→ Changes in a satellite's attitude cause the angles θ, ϕ & ψ in figure 2. to vary as the X, Y, & Z axes move relative to fixed reference axes X_R, Y_R and Z_R.

→ The Z axis is usually directed toward a reference point on earth, called as Z-axis intercept.

→ The location of Z-axis intercept defines the pointing of the satellite antennas.

→ The Z-axis intercept point may be moved to repoint antenna beam ~~when the~~ by changing the attitude of satellite ~~is changed~~ with the attitude control system.

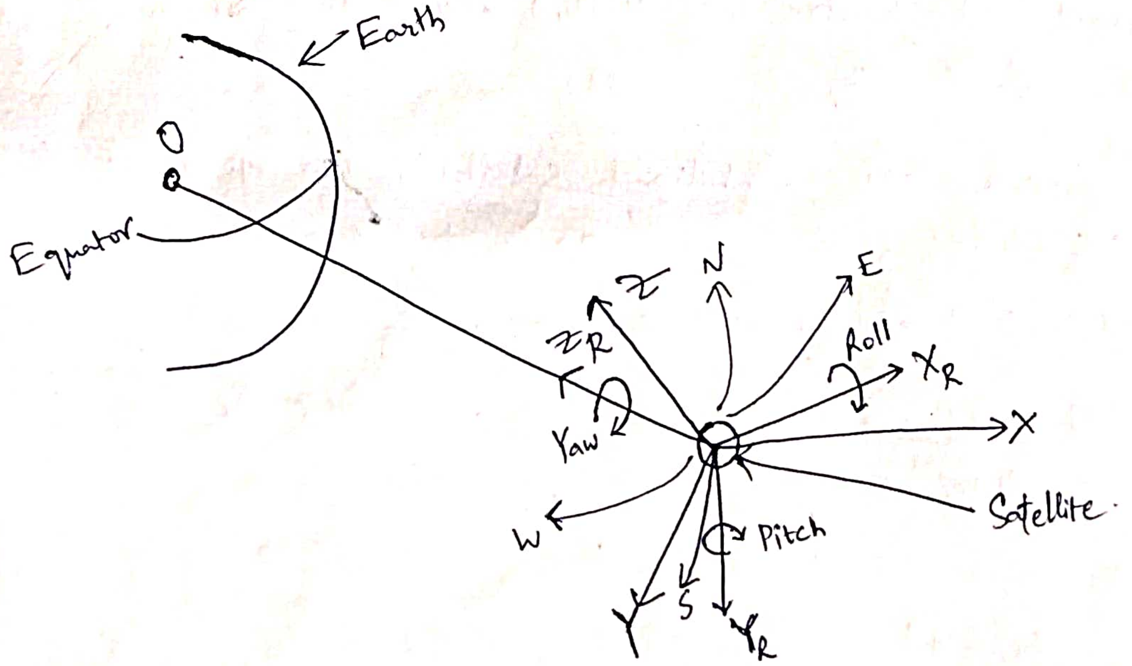


fig 1. forces on a Satellite

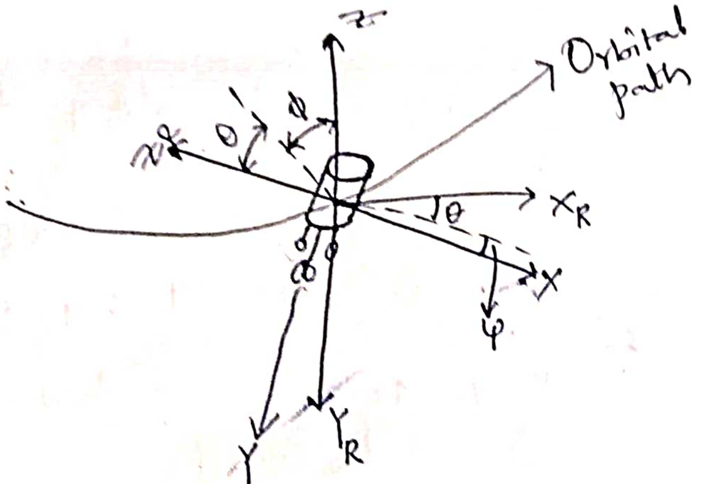


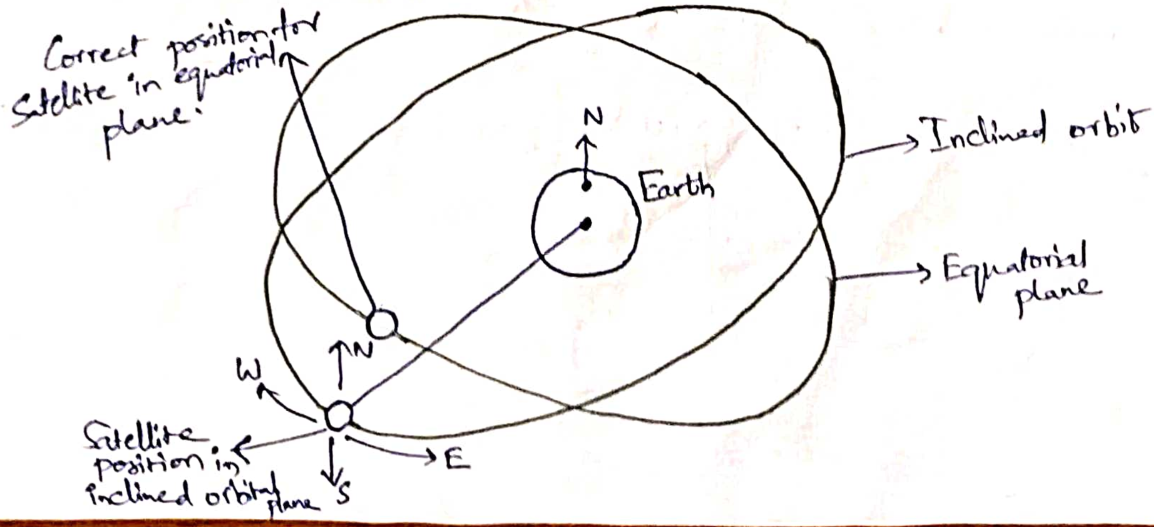
fig2. Relationship between axes of a Satellite.

Orbit Control System :-

→ The gravitation forces of moon and the Sun causes inclination of the orbital plane. There are many other smaller forces that act on the satellite causing the orbit to change.

→ It is the function of the orbit control system to return it to the correct orbit.

→ For the orbit to be truly geostationary, it must lie in the equatorial plane, be circular and have correct altitude.



→ Gas jets that can impart velocity changes along the three references axes of the satellite are required.

→ If the orbit is not circular, a velocity increase or decrease will have to be made along the orbit, in X-axis direction.

→ On a spinning satellite, this is achieved by pulsing the radial jets when they point along the x-axis.

→ On a three-axis stabilized satellite, there will usually be two pairs of X-axis jets acting in opposite directions, one pair of which will be operated for a predetermined length of time to provide the required velocity change.

→ The orbit of a geostationary satellite remains approximately circular for long periods of time and does not need frequent velocity corrections to maintain circularity.

Power Systems :-

→ All satellites obtain their electrical power from solar cells, which convert incident sunlight into electrical energy.

→ The sun is a powerful source of energy. In the total vacuum of outer space at geostationary altitude, the radiation falling on a satellite has an intensity of 1.39 kW/m2.

→ Solar cells do not converty all this incident energy their efficiency is typically 20 to 25% at beginning of life (BOL) but falls with time because of aging of cells.

→ Since sufficient power must be available at end of life (EOL) of the satellite to supply all the subsystems, about 15% extra area of solar cells is usually provided as an allowance for againg.

→ A spin-stabilized satellite usually has a cylindrical body covered in solar cells.

→ Due to which half of the cells are not illuminated at all, and at the edges of the illuminated half, results in electrical power being generated.

→ The cells that are not illuminated by sunlight face cold space, which causes them to cool down and also increases their efficiency somewhat

→ Early satellites were of small dimensions and had relatively small areas of solar cells.

→ More recently, large communications satellites for direct broadcast operation generate up to 6KW from solar power.

→ A three-axis stabilized satellite can make better use of its solar cell area, since the cells are arranged on flat panels that can be rotated to maintain normal incidence of the sunlight and can generate power in excess of 10KW.

→ Solar sails must be rotated by an electric motor once per 24hrs to keep the cells in full sunlight.

→ This causes the cells to heat up, typically to 50° to 80°c which causes a drop in output voltage. In the spinner design, the cells cool down when in shadow and run at 20° to 30°c, with higher efficiency.

→ The satellite must carry batteries to power the subsystems during launch and during eclipses.

→ Batteries are usually of the nickel-hydrogen type which do not gas when charging and have good reliability and long life and can be safely discharged to 70% of their capacity.

→ Sensors on the batteries, power regulator and solar cells monitor temperature, voltage and current and send these data to controlling earth station via telemetry downlink.

Telemetry, Tracking, Command and Monitoring :

→ The TTC&M system is essential to the successful operation of a communications satellite.

→ It is part of the satellite management task, which also involves an earth station, usually dedicated to that task.

→ The main functions of satellite management task are to control the orbit and attitude of satellite, monitor the status of all sensors and subsystems on the satellite,

→ The TTC&M earth station may be owned & operated by the satellite owner or it may be owned by a third party & provide TTC&M services under contract.

→ On large geostationary satellites. some repointing of individual antennas may be possible under the command of TTC&M system where tracking is performed primarily by the earth station.

→ Figure 1. illustrates the functions of a controlling earth station.

① Telemetry and Monitoring System :

→ The monitoring system collects data from many sensors within the satellite and sends these data to the controlling earth station.

→ There may be several hundred sensors located on the satellite to monitor pressure in the fuel tanks, voltage and current in the power conditioning unit, current drawn by each subsystem, critical voltages and

Currents in the communications electronics.

→ The temperature of many of the subsystems is important and must be kept within predetermined limits, so many temperature sensors are fitted.

→ The sensor data, the status of each subsystem and the positions of switches in the communication system are reported back to the earth by the telemetry system.

→ The devices used to maintain attitude are also monitored via the telemetry link; this is essential in case one should fail and cause the satellite to point in the wrong direction.

→ The faulty unit must then be disconnected and a spare brought in via command system or some other means of controlling attitude devised.

→ Telemetry data are usually digitized and transmitted as phase shift keying (PSK) of a low power telemetry carrier using time division techniques.

→ A low data rate is normally used to allow the receiver at the earth station to have a narrow bandwidth and thus maintain a high carrier to noise ratio.

→ The entire TDM frame may contain thousands of bits of data and take several seconds to transmit.

→ At the controlling earth station a computer can be used to monitor, store and decode the telemetry data so that the status of any system or sensor on the satellite can be determined immediately by the controller on the earth.

→ Alarms can also be sounded if any vital parameter goes outside allowable limits.

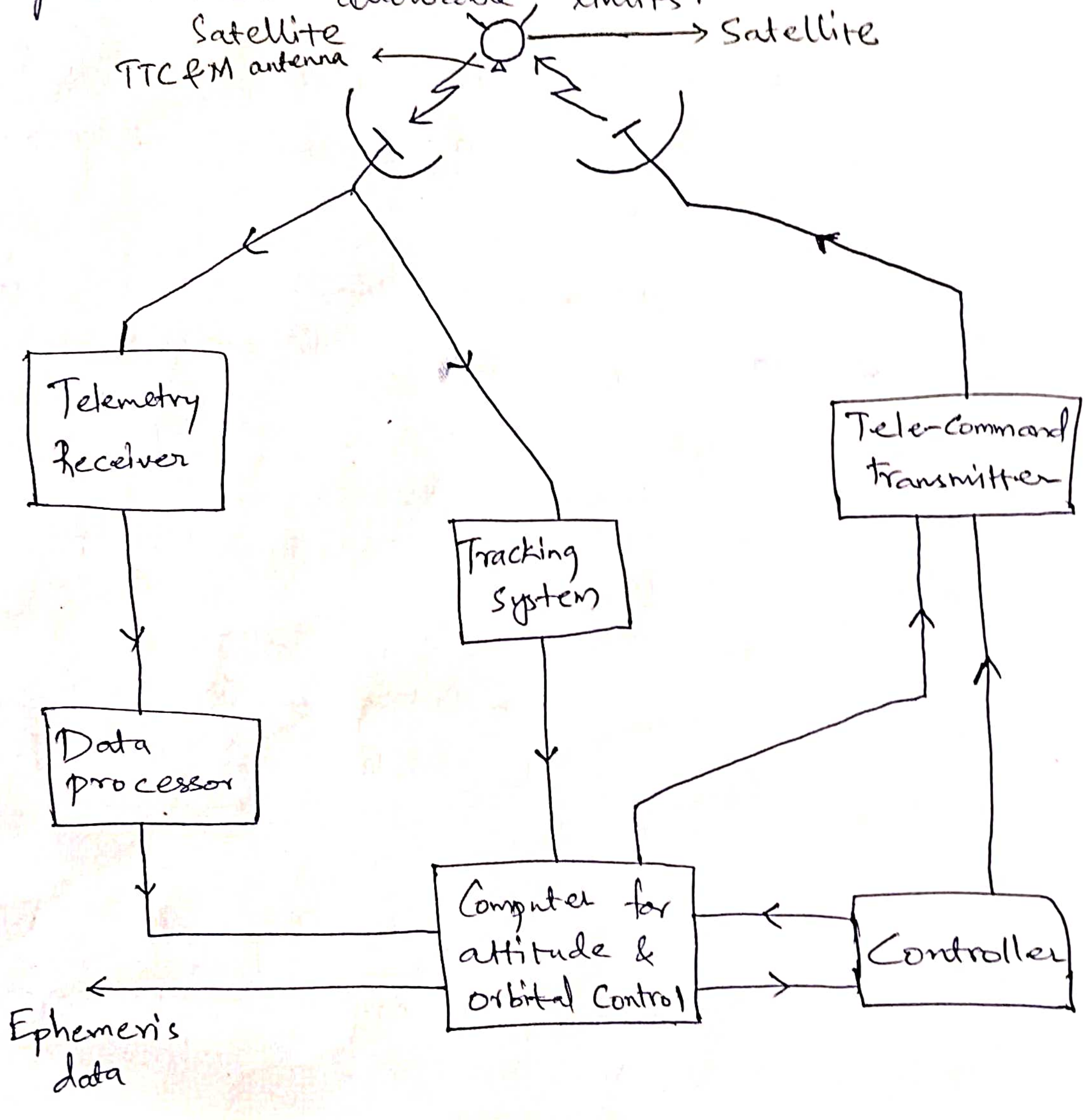


figure 1. Typical tracking, telemetry, command and monitoring system.

(2) Tracking :- A number of techniques can be used to determine the current orbit of a satellite.

→ Velocity and acceleration sensors on the satellite can be used to establish the change in orbit from the last known position, by integration of the data.

→ The earth station controlling the satellite can observe the Doppler shift of the telemetry received signal or carrier transmitter signal to determine the rate at which range is changing.

→ Active determination of range can be achieved by transmitting a pulse, or sequence of pulses, to the satellite and observing the time delay before the pulse is received again.

→ The propagation delay in the satellite transponder must be accurately known.

→ With precision equipment at the earth stations, the position of satellite can be determined within 10min.

(3) Command :-

→ A secure and effective command structure is vital to the successful launch and operation of any communications satellite.

→ The command system is used to make changes in attitude and corrections to the orbit and to control the communication system.

→ During launch, it is used to control the firing, to extend solar sails and antennas of a satellite.

→ The command structure must possess safeguards against unauthorized attempts to make changes to the satellites operation and also wrong operation of a control due to error in a received data.

→ There will be encryption for commands and responses to provide security in command system.

→ In figure 1., It is shown that a typical system of this type will originate commands at control terminal of computer.

→ The control code is converted into a command word, which is sent in a TDM frame to the satellite.

→ After checking for validity in the satellite, the word is sent back to the control station via the telemetry link where it is checked again in the computer.

→ If it is found to have been received correctly an execute instruction will be sent to satellite so that the command is executed.

→ The entire process may take 5 or 10 sec, but minimizes the risk of error commands causing a satellite malfunction.

→ With these controls, ~~the~~ satellite can be injected into geostationary orbit, turned to face the earth, etc, and also used to eject satellite from orbit and to switch off all transmitters when the satellite reaches to end of its useful life.

Satellite Antennas :

→ Four Main types of antennas are used on satellites. These are

1. Wire antennas : monopoles and dipoles.
2. Horn antennas.
3. Reflector antennas.
4. Array antennas.

→ Wire antennas are primarily used at VHF and UHF to provide Communications for the TTC&M systems.

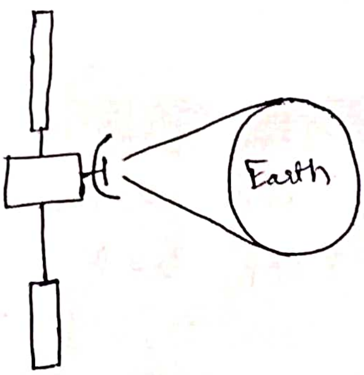
→ They are positioned with great care on the body of the satellite in an attempt to provide omni-directional coverage.

→ A useful principle in antenna theory is reciprocity. Reciprocity means that an antenna has the same gain and pattern at any given frequency whether it transmits or receives.

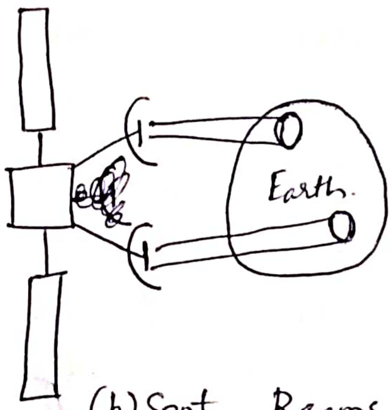
→ An antenna pattern measured when receiving is identical to the pattern when transmitting.

→ However, a satellite antenna is used to provide coverage of a certain area, or zone on the earth's surface.

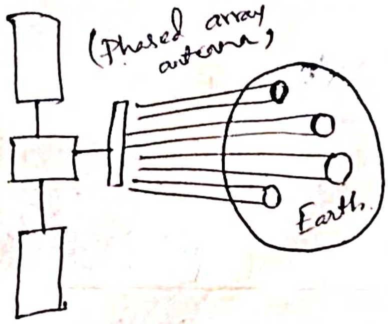
→ Fig 1. Shows typical satellite antenna coverage zones.



(a) Global Beam
(Horns antenna)



(b) Spot Beams.
(Reflector antennas)



(c) Multiple spot beams and scanning beams.

→ However, a satellite antenna is used to provide coverage of a certain area or zone on earth's surface.

→ Horn Antennas. are used at microwave frequencies when relatively wide beams are required as for global coverage.

→ A Horn is a flared section of waveguide that provides an aperture several wavelengths wide and a good match between the waveguide impedance and free space.

→ Horn and Reflectors antennas are best examples that launch a wave into free space from a waveguide.

→ It is difficult to obtain gains much greater than 23dB or beamwidths narrower than about 10° with Horn Antennas.

→ For higher gains or narrow beamwidths a reflector antenna or array must be used.

→ Reflector antennas are usually illuminated by one or more horns and provide a larger aperture.

→ It is important to choose a reflector profile that has equal path lengths from feed to the aperture, so that all the energy radiated by feed and reflected by reflector reaches the aperture with the same phase angle. ~~and creates a uniform phase~~

→ One reflector shape that achieves this with a point source of radiation is paraboloid with a feed placed at its focus.

→ Paraboloid is the basic shape for most reflector antennas and is commonly used for earth station antennas.

→ Satellite antennas often use modified paraboloid reflector profiles to tailor the beam patterns to a particular coverage zone.

→ Phased array antennas are also used on satellites to create multiple beams from a single aperture and have been used by "Globalstar" to generate upto 16 beams for its LEO mobile telephone systems.

→ The following approximate relationships will be used here to guide the selection of antennas for a satellite communications.

→ An aperture antenna has a gain G given by

$$\boxed{G = \eta_A 4\pi A/\lambda^2} \quad \text{—— (1)}$$

A → area of antenna aperture (m)

λ → operating wavelength (m)

η_A → aperture efficiency of antenna.

→ For reflector antennas, η_A ranges 55 to 68%.

→ For Horn antennas, η_A ranges 65 to 80%.

→ If the aperture is circular, then gain G is given by

$$\boxed{G = \eta_A (\pi D/\lambda)^2} \quad -(2)$$

D → Diameter of circular aperture (m)

→ The Beamwidth of an antenna is related to the aperture dimension in the plane in which the pattern is measured and is given by,

$$\boxed{\theta_{3dB} \approx 75\lambda/D \text{ degrees}} \quad -(3)$$

θ_{3dB} → Beamwidth between half power points of the antenna pattern

D → aperture dimension (m)

→ Since both eq. (2) & (3) contain antenna dimension ~~patt~~ parameters, the gain and beamwidth of an aperture antenna are related.

→ For antennas with $\eta_A \approx 60\%$, the gain is approximately,

$$\boxed{G \approx 33,000 / (\theta_{3dB})^2} \quad -(4)$$

G → is not in decibels.

→ Example:-

(1) What are the dimensions and gain of a horn antenna which give circularly symmetric beam with a 3-dB beamwidth of 17° to provide global coverage at 4 GHz?

Sol:- ~~For circular aperture~~

Given,

$$f = 4\,GHz$$

$$\theta_{3dB} = 17°$$

W.K.T.,

$$\theta_{3dB} = 75\lambda/D$$

$$\Rightarrow D/\lambda = 75/(\theta_{3dB})$$

$$D/\lambda = \frac{75}{17} = 4.4 \quad - \text{I}$$

Since, $f = 4\,GHz$

$$\lambda = \frac{c}{f} = \frac{3\times10^8}{4\times10^9} = 0.075\,m \quad - \text{II}$$

Sub. II in I

$$D/0.075 = 4.4$$

$$\Rightarrow D = 0.33\,m$$

$$\rightarrow G \approx 33{,}000/(\theta_{3dB})^2$$

$$\therefore \quad G \approx 33{,}000/(17)^2 \approx 114$$

In dB, gain is approximately 20dB for this horn antenna.

Communications Subsystems :-

→ A communications satellite exists to provide a platform in geostationary orbit for the relaying of voice, video and data communications.

→ All the subsystems on the satellite exist to support the communications system, which may represent only a small part of the volume, weight and cost of the satellite in orbit.

→ The growth in capacity is well illustrated in the Figure 1 for Intelsat system.

→ Successive satellites have become larger, heavier and more costly but the rate at which traffic capacity has increased has been much greater.

→ The satellite transponders have limited output power and the earth stations are at least 36,000 km away from them, so the received power level, even with large aperture earth station antennas, is very small and rarely exceeds 10^{-10} W.

→ With low power transmitters, narrow receiver bandwidths have to be used to maintain the required signal-to-noise ratios for the system to perform satisfactorily.

→ Early communications satellite were fitted with transponders of 250 or 500 MHz bandwidth, but had low gain antennas and transmitters of 1W or 2 W output power, where earth stations could not achieve adequate signal-to-noise ratios.

→ Later generations of satellites have transponders with greatly increased output power upto 200 W for DBS-TV satellites and have steadily improved in bandwith utilization.

→ For example, the total channel capacity of a satellite that uses a 500-MHz band at 6/4 GHz can be increased only if the bandwidth can be increased or reused.

→ The trend in high-capacity satellites has been to reuse the available bands by employing several directional beams at the same frequency (spatial frequency reuse) and orthogonal polarizations at the same frequency (polarization frequency reuse).

→ Large GEO satellites also use both 6/4 GHz and 14/11 GHz bands to obtain more bandwidth.

→ The designer of a satellite communication system is not free to select any frequency and bandwidth he or she chooses.

→ International agreements restrict the frequencies that may be used for particular services.

→ The 500-MHz bands originally allocated for 6/4 and 14/11 GHz satellite communications have become very congested and are now completely filled for some segments of the GEO orbit.

→ Extension of the bands to 1000MHz will eventually provide greater capacity as the new frequencies come into use.

→ Many systems now use 14/11 GHz for TV broadcast and 30/20 GHz systems for Internet-like services.

→ Satellite systems designed for Ku band (14/11 GHz) and Ka band (30/20 GHz), have narrower antenna beams, and better control of coverage patterns than satellites using in C-band (6/4 GHz).

Transponders :

→ Signals (Known as carriers) transmitted by an earth station are received at the satellite by either a zone beam or a spot beam antenna.

→ Zone beams can receive from transmitters anywhere within the coverage zone, whereas spot beams have limited coverage.

→ The received signal is often taken to two low noise amplifiers and is recombined at their output. If either amplifier fails, the other one can still carry all the traffic.

→ figure 3.10 shows a simplified block diagram of a satellite communication subsystem for the 6/4 GHz band. The 500-MHz bandwidth is divided up into channels, often 36MHz wide, which are each handled by a seperate transponder. A transponder consists of a band-pass filter to select the particular channel's band of frequencies, a down converter to change the frequency from 6GHz at the input to 4 GHz at the output, and an output amplifier. The communication system has many transponders some of which may be spares; typically 12 to 44 active transponders are carried by a high-capacity satellite. The transponders are supplied with signals from one or more receive antennas and send their outputs to a switch matrix that directs each transponder band of frequencies to the appropriate antenna or antenna beam.

In the case of the Intelsat global system, this could result in a requirement for as many as 100 transponders per satellite. As a compromise, 36 MHz has been widely used for transponder bandwidth, with 54 and 72 MHz adopted for some satellite (3)

Many domestic satellites operating in the 6/4 GHz band carry 24 active transponders. The center frequencies of the transponders are spaced 40 MHz apart, to allow guard bands for the 36 MHz filter skirts. With a total of 500 MHz available, a single polarization across the satellite can accommodate 12 transponders band. When frequency reuse by orthogonal polarization is adopted, 24 transponders can be accommodated in the same 500 MHz bandwidth

The reuse is achieved through microwave switch interconnections between sub beams

Figure 3.11 shows a simplified diagram of the communication system carried by INTELSAT V satellites. The later series of Intelsat satellites use a similar arrangement. The bulk of the traffic is carried by the 6/4 GHz section, with a total bandwidth of 2000 MHz avaiable by frequency reuse. The switch matrix ~~and~~ allows a very large number of variations in connecting the 6-GHz receivers to the 4-GHz transmitters.

When more than one signal shares a transponder (using frequency division multiple access, FDMA) the power amplifier must be run below its maximum output power to maintain linearity.

The degree to which the transmitter output power is reduced below its peak output is known as output backoff. in FDMA systems, 2 to 7 dB of output backoff is typically used.

Backoff results in a lower down link carrier-to-noise ratio at the earth station with FDMA when multiple accesses to each transponder are required. Time division multiple access (TDMA) can theoretically be used to increase the output power of transponders by limiting the transponder to a single access

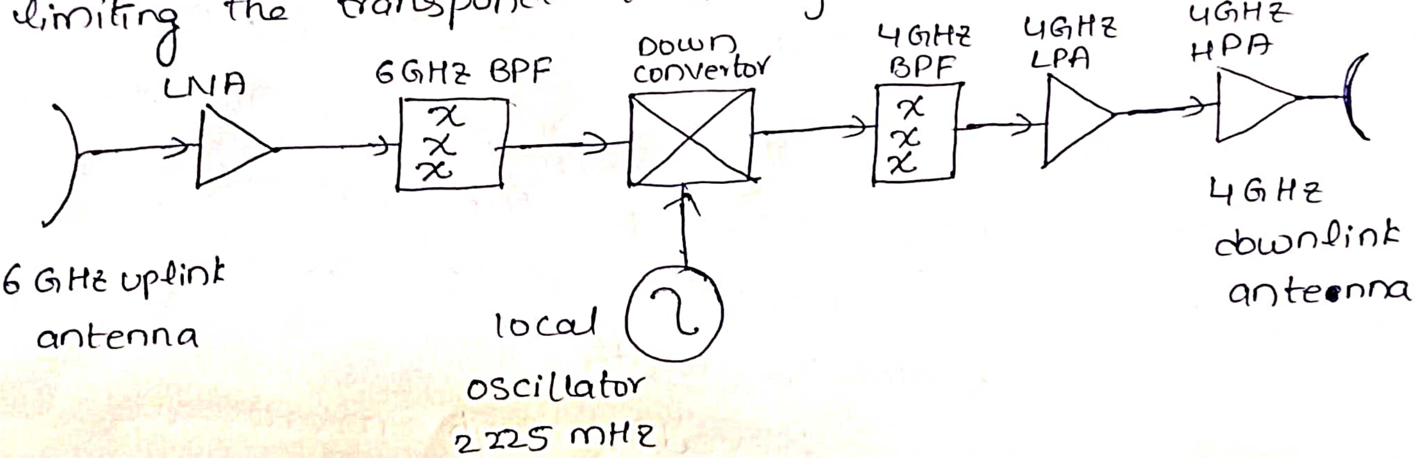


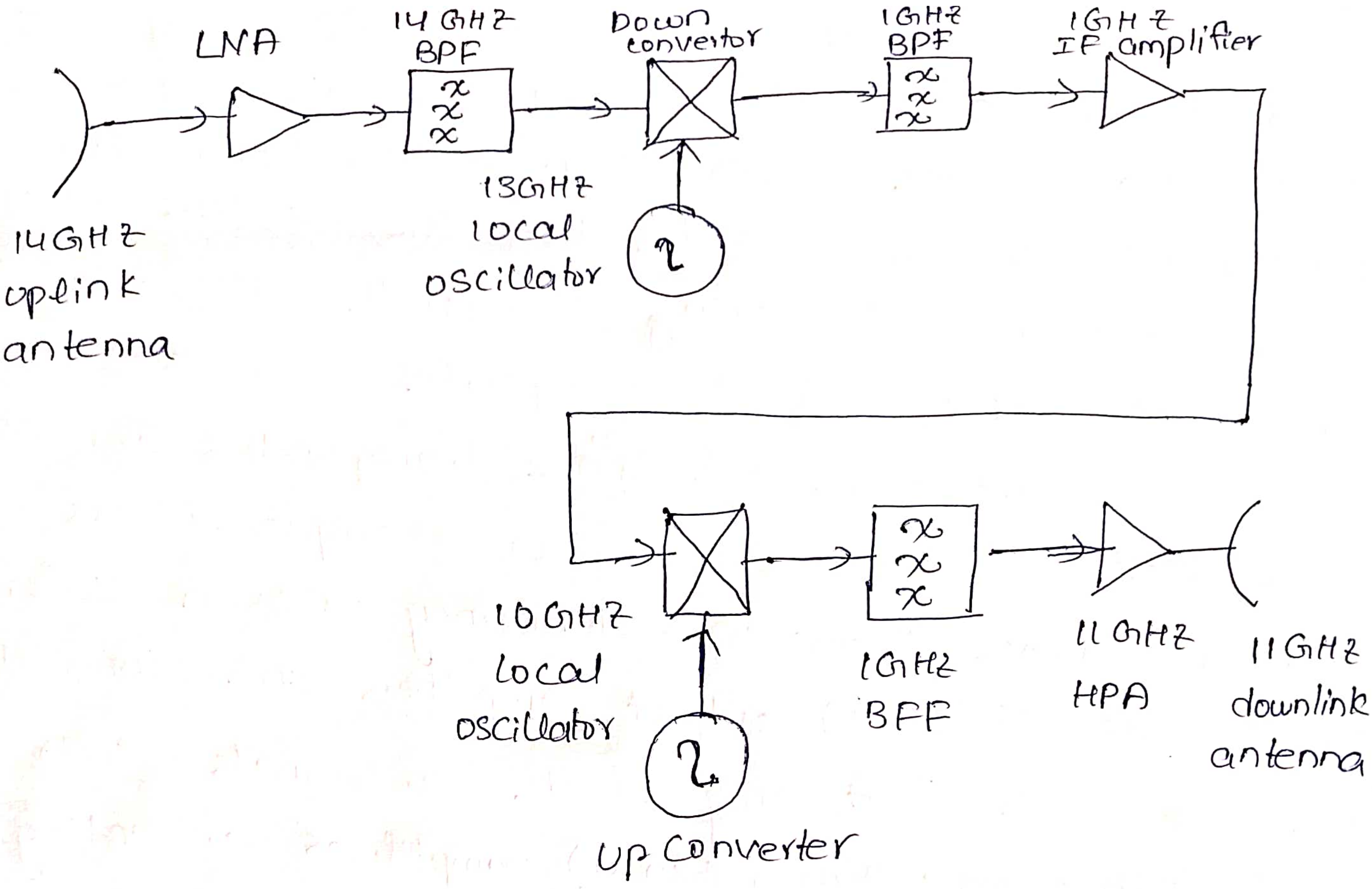
Figure 3.12 Simplified single conversion transponder (bent pipe) for 6/4 GHz band

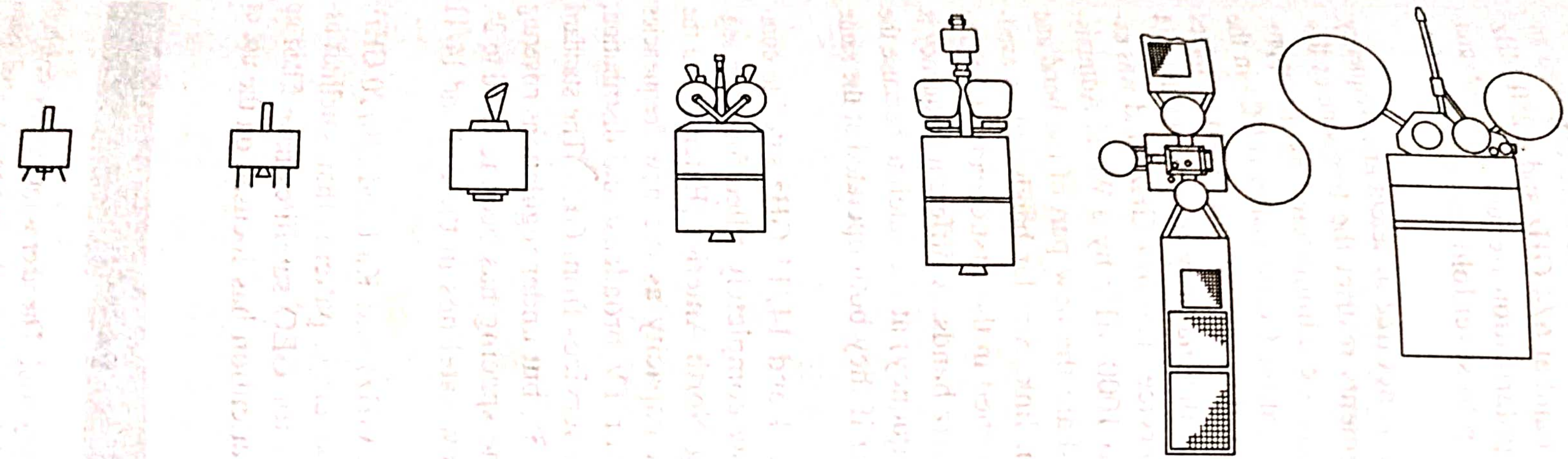
Figure 3.12 shows a typical single conversion bent pipe transponder of the type used on many satellites for the 6/4 GHz band. The output power amplifier is usually a solid state power amplifier (SSPA) unless a very high output power (>50W) is required, when a traveling wave tube amplifier (TWTA) would be used. The local oscillator is at 2225 MHz to provide the appropriate shift in frequency from the 6-GHz uplink frequency to the 4-GHz down link frequency, and the band-pass filter the mixer removes unwanted frequencies resulting from the down-conversion operation. The attenuator can be controlled via the uplink command system to set the gain of the transponder.

The lifetime of HPAS is limited, and they
represent the least reliable component is most
transponders. providing a spare HPA in each transponder
greatly increases the probability that the satellite will
reach the end of its working life with all its
transponders still operational. Transponders can also be
arranged so that there are spare transponders available
in the event of a total failure. For enample, it is
common to have 16 for 10 redundancy or even 14 for
10. That is, 16 (or 14) output amplifiers are connected
in a ring such that any of the 10 Signals can
pass through them. Thus, 6 (or 4) amplifiers are acting
as back-up amplifiers while 10 are on line

Transponders for use in the 14/11-GHz bands
normally employ a double frequency conversion scheme
as illustrated in figure 3.15. It is easier to make
filters, amplifiers, and equalizers at an intermediate
frequency (IF) such as 1100-MHz than at 14 or
11 GHz, so the incoming 14-GHz carrier is translated
to an IF of around 1 GHz. The amplification and
filtering are performed at 1 GHz and a relatively
high-level carrier is translated back to 11GHz for
amplification by the HPA

Stringent requirements are placed on the
filters used in transponders, since they must provide
good rejection of unwanted frequencies


LNA
14 GHZ BPF
Down convertor
1GHZ BPF
1GHZ IF amplifier
13GHZ local oscillator
14GHZ uplink antenna
10GHZ local oscillator
1GHZ BFF
11 GHZ HPA
11GHZ downlink antenna
up converter



Spacecraft	INTELSAT I	INTELSAT II	INTELSAT III	INTELSAT IV	INTELSAT IV-A	INTELSAT V	INTELSAT VI
Year of first launch	1965	1967	1968	1971	1975	1980	1986 (planned)
Dimensions	0.71 m dia × 0.59 m high	1.42 m dia × 0.67 m high	1.42 m dia × 1.98 m high	2.38 m dia × 7.01 m high	2.38 m dia × 7.01 m high	15.27 m across solar sails × 6.71 m high	3.6 m dia × 11.7 m high
On orbit weight	34 kg	76 kg	152 kg	595 kg	786 kg	1020 kg	1800 kg
End of life primary power	46 W	85 W	125 W	569 W	708 W	1220 W	2100 W
Total bandwidth	50 MHz	130 MHz	360 MHz	450 MHz	720 MHz	2250 MHz	3360 MHz
Notional capacity two-way telephone circuits	240	240	1500	5000	11,000 plus 2 TV channels	24,000 plus 2 TV channels	33,000 plus 2 TV channels
Design lifetime	1.5 years	3 years	5 years	7 years	7 years	10 years	10 years
Spacecraft cost	$3.6 M	$3.5 M	$4.5 M	$14 M	$18 M	$25 M	$140 M (first five satellites)
Launch cost	$4.6 M	$4.6 M	$6 M	$20 M	$20 M	$23 M	?
Cost per telephone circuit year	$23,000	$11,000	$1,600	$810	$494	$200	?
Contractor	Hughes	Hughes	TRW	Hughes	Hughes	Ford Aerospace	Hughes

FIGURE 3.9 Illustration of the growth in size and weight of Intelsat satellites over 3 decades.

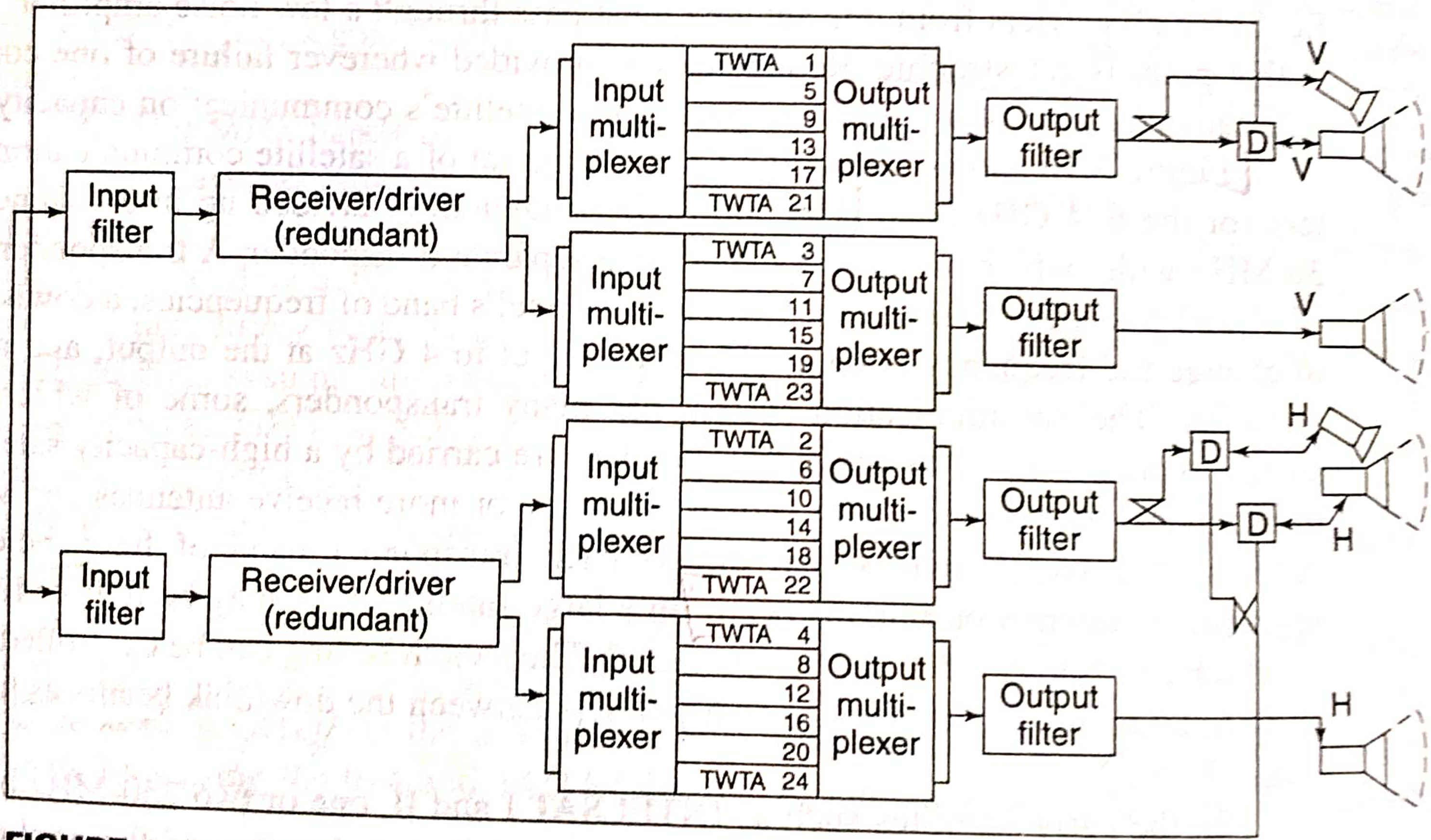


FIGURE 3.10 Transponder arrangement of RCA's SATCOM satellites and frequency plan. The translation frequency is 2225 MHz. [Reproduced with permission from W. H. Braun and J. E. Keigler, "RCA Satellite Networks: High Technology and Low User Cost," *Proceedings of the IEEE, 72, 1483–1505* (November 1984). Copyright © 1984 IEEE.]

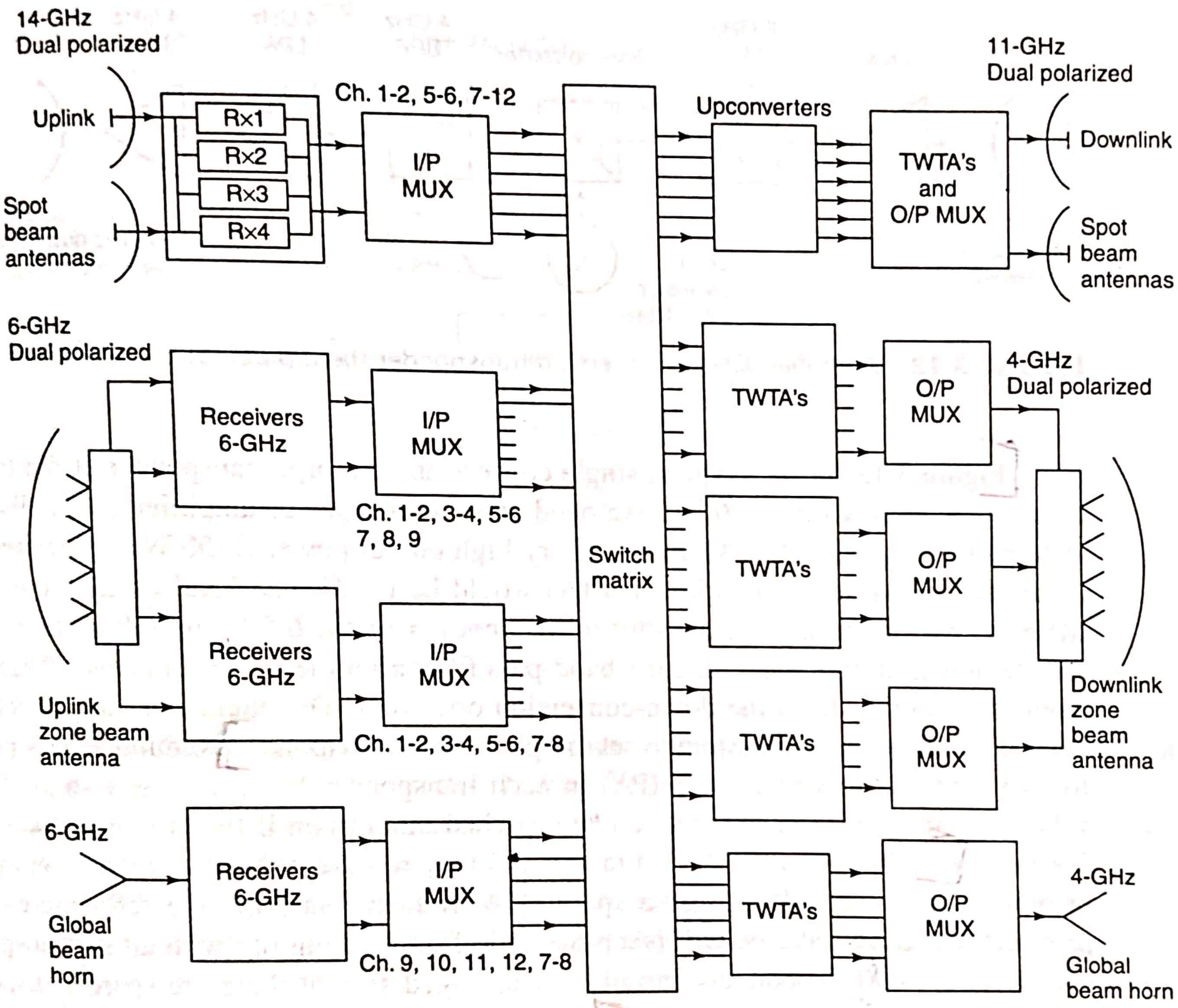


FIGURE 3.11 Simplified block diagram of an INTELSAT V communication system. Note that the switch matrix allows many possible interconnections between uplink beams and downlink transmitters. (Courtesy C. F. Hoeber, Ford Aerospace and Communications Corp.)