ECE 539
Satellite and Mobile Communication

Assist. Prof. Dr. Şenol Gülgönül

2024 Fall

Manager of Control&Electronic Systems
BMC Power · Full-time
2017 - 2022 · 5 yrs

-Managing Engine Control Unit (ECU) and (Transmission Control Unit)
development of ALTAY Main Battle Tank and other military diesel ...see more

Skills: OpenECU · MIL-STD-461 · MIL-STD-464 · MIL-STD-1275 · MIL-STD-810 · ISO 26262 · ECE R10 · IPC 620 · Simulink · Embedded Systems · Project

Parttime Instructor
Çankaya Üniversitesi · Part-time
2017 · Less than a year

ECE 439: Satellite and Mobile Communication Systems
ECE 246: Fundamentals of Electronics

Skills: Electronics · Satellite Communications (SATCOM)

Technical Manager
Turksat Uydu Haberleşme Kablo TV ve İşletme A.Ş. · Full-time
2004 - 2016 · 12 yrs
Ankara, Turkey

-VP of Satellite Operations: Involved in Turksat 4A&4B, Turksat 5A&5B and
Turksat 6A satellite projects projects. Daily operation of teleport ...see more

Skills: Satellite Systems Engineering · Satellite Ground Systems · Satellite TV
Global Navigation Satellite System (GNSS) · Satellite Communications

Network Manager
KoçSistem · Full-time
Mar 2000 - Jul 2000 · 5 mos

Network Manager of Cisco routers

Skills: Cisco Routers

Senior Network Engineer
TurkNet · Full-time
1996 - 1999 · 3 yrs

Network manager of Turnet which was the first commercial internet backbone of
SATCOM, Cisco routers

Skills: VSAT · Cisco Routers · Satellite Communications (SATCOM)

Chief Engineer
Turk Telekom · Full-time
1993 - 1995 · 2 yrs

Chief Ground Control Systems engineer of Turksat Satellite Control Center. The first communication sate
of Turkey: Turksat-1A, Turksat-1B and Turksat-1C

Bilkent University
Bachelor of Science - BS
1986 - 1992

Gebze Technical University
Master's degree
1996 - 1998

Sakarya University
Doctor of Philosophy - PhD
2009 - 2014

Development of a LEO communication CubeSat
AR Aslan, HB Yağcı, ME Umit, A Sofyalı, ME Bas, MS Uludag, OE Ozen, ...
2013 6th International Conference on Recent Advances in Space Technologies ...

Communication satellite payload redundancy reconfiguration
S Gulgonul, E Koklukaya, I Erturk, AY Tesneli
2012 IEEE First AESS European Conference on Satellite Telecommunications ...

Thermal control design of TUSAT
M Bulut, S Gülgonul, N Sozbir
6th International Energy Conversion Engineering Conference (IECEC), 5751

An antenna array for Ku band satellite reception
AF Yagli, M Gokten, L Kuzu, HH Ertok, S Gulgonul
2015 31st International Review of Progress in Applied Computational ...

Battery thermal design conception of Turkish satellite
M Bulut, S Demirel, S Gulgonul, N Sozbir
6th International Energy Conversion Engineering Conference (IECEC), 5787

TURKSAT-3USAT: A 3U communication CubeSat with passive magne
AR Aslan, A Sofyali, E Umit, C Tola, I Öz, S Gülgönül
Proceedings of 5th International Conference on Recent Advances in Space ...

Properties and performance comparison of electrical power sub-syste
communication satellite
S Demirel, E Sanli, M Gokten, AF Yagli, S Gulgonul
2012 IEEE First AESS European Conference on Satellite Telecommunications ...


CSG

ABOUT

- Satellite Communications Systems: Systems, Techniques and Technology, 5th Edition, Gerard Maral, Michel Bosquet

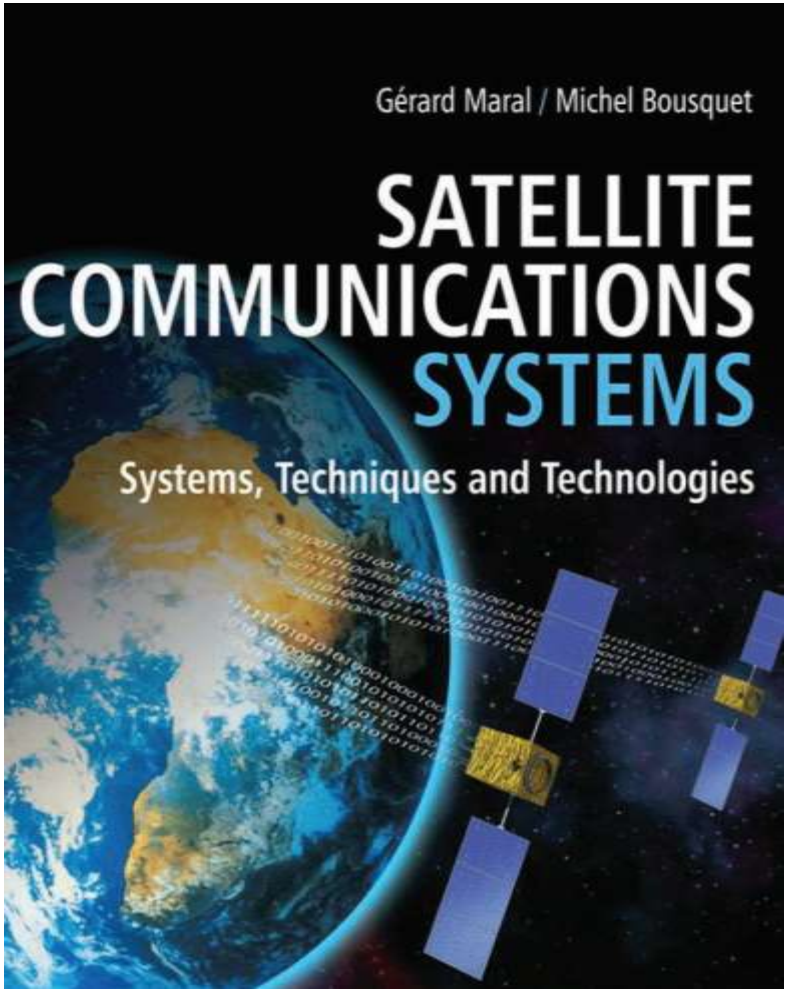
- Grades:

20% Midterm

20% Project

60% Final

- Additional Resources:
- Inelsat Earth Station Technology



Course Plan

- Communication Satellites
- Satellite Orbits
- Midterm
- Term Project
- Satellite Communication
- Final

Satellites

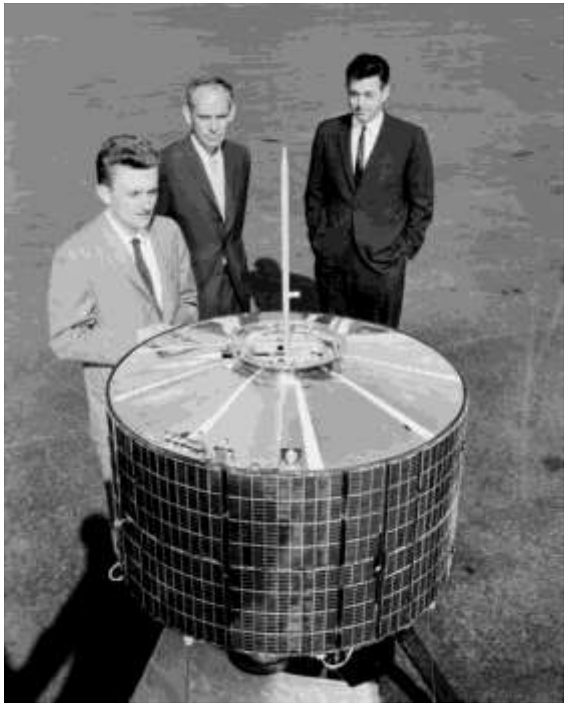
- Satellites are electronic systems moving on their orbit around the Earth for different purposes such as communication, GPS, Earth Observation, Meteorology etc

Satellites

- Sputnik-1 was the first satellite launched on 4 October 1957

Satellites

- Syncom-2 is the first communication satellite, launched on July 26, 1963



Satellites by Application

Satellites can be categorized according to their usages:

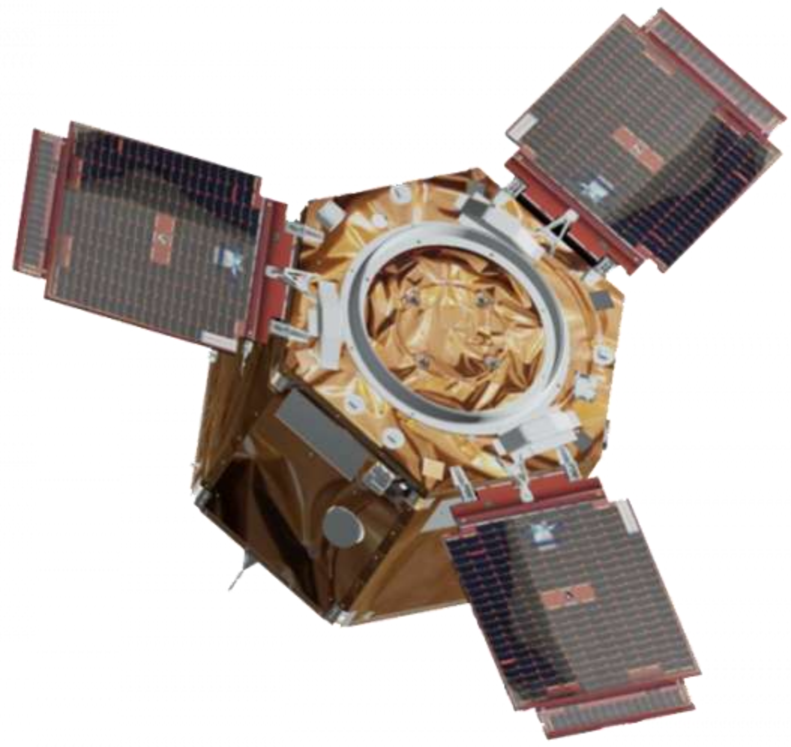
- Observation Satellites
- Navigation Satellites
- Meteorology Satellites
- Scientific Satellites
- Cubesats
- Communication Satellites

Observation Satellites

- Observation satellites can take images of Earth up to 10cm resolution.

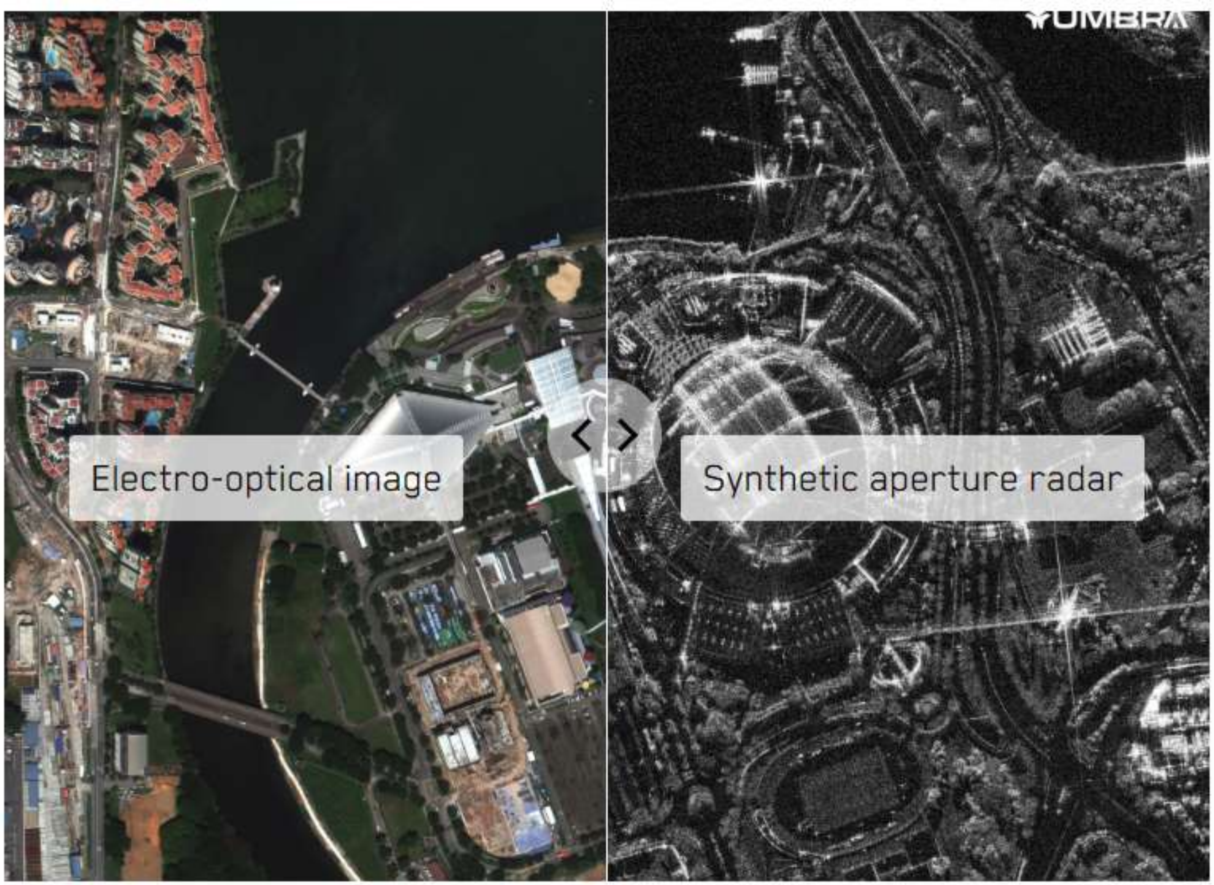
Observation Satellites

- Göktürk-1 (launch 2016)
- Göktürk-2 (launch 2012)



Observation Satellites

- While electro-optic satellites can get images only at clear sky Synthetic Aperture Radar (SAR) Satellites can take images during day/night



Satellite Navigation – GPS - How It Works

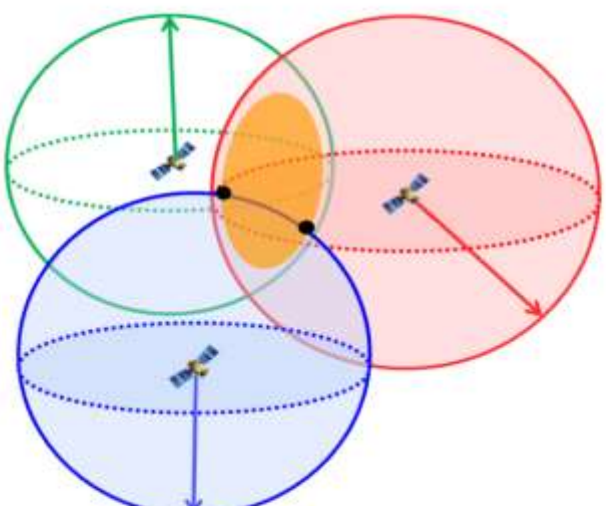
- 31 Global Positioning System (**GPS**) satellites developed and operated by the United States
- other constellations are **GLONASS** developed and operated by the Russian Federation, **Galileo** developed and operated by the European Union, and **BeiDou**, developed and operated by China
- The basic GPS service provides users with approximately 7.0 meter accuracy, 95% of the time, anywhere on or near the surface of the earth
- signals from at least four satellites, to determine their location and time
- GPS satellites carry atomic clocks that provide extremely accurate time

Satellite Navigation – GPS - How It Works

- With information about the ranges to three satellites and the **location of the satellite when the signal was sent**, the receiver can compute its own three-dimensional position.
- An atomic clock synchronized to GPS is required in order to compute ranges from these three signals.
- However, **by taking a measurement from a fourth satellite, the receiver avoids the need for an atomic clock**.
- Thus, the receiver uses four satellites to compute latitude, longitude, altitude, and time

Navigation Satellites

Two spheres intersection is a circle. A circle and sphere intersection is two points. Fourth satellite solves the ambiguity



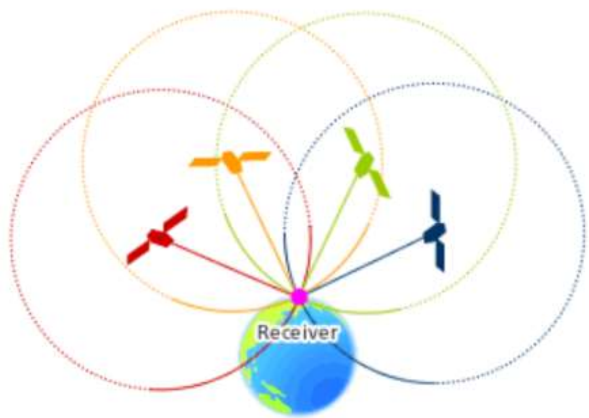
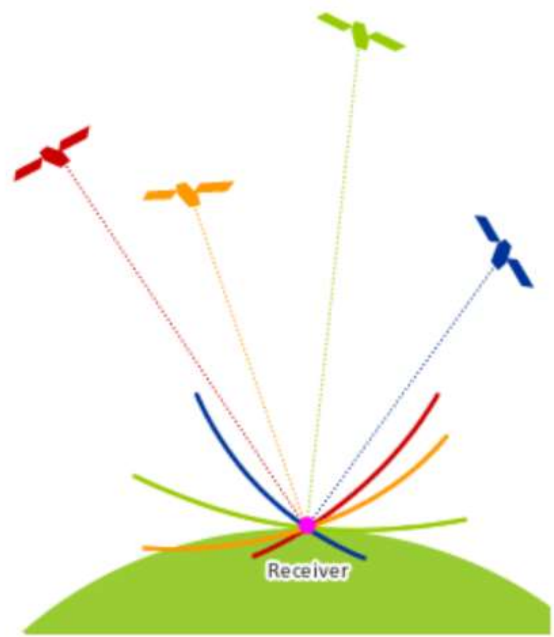


Image of distance between you and four satellites



A point where four distances meet

GPS Signal

1. **Satellite Positioning Data:** The satellites broadcast information about their own position and the time the signals were transmitted. This information is crucial for the GPS receiver to calculate its distance from each satellite.
2. **Timestamps:** The signals include precise timestamps indicating when the signal was transmitted by the satellite. This timing information is crucial for calculating the distance between the satellite and the GPS receiver.

Navigation Satellites

The equations that are solved to approximate a receiver's location using GPS are:

$$(x - A1)^2 + (y - A2)^2 + (z - A3)^2 = \left(c(t1 - d)\right)^2$$
$$(x - B1)^2 + (y - B2)^2 + (z - B3)^2 = \left(c(t2 - d)\right)^2$$
$$(x - C1)^2 + (y - C2)^2 + (z - C3)^2 = \left(c(t3 - d)\right)^2$$
$$(x - D1)^2 + (y - D2)^2 + (z - D3)^2 = \left(c(t4 - d)\right)^2$$

where x, y, and z are the rectangular coordinates of the receiver, A, B, and C are the coordinates of the satellites, d is the difference in time between the receiver and the satellite's clocks, and t is the travel time for the signal. c is speed of light.

c.ti is also called as pseudo range
c.d is also called as Receiver clock bias in meters

Solving GPS Equations

```
A=[15600,7540,20140];
B=[18760,2750,18610];
C=[17610,14630,13480];
D=[19170,610,18390];
t=[0.07074,0.07220,0.07690,0.07242];
Guess=[0,0,6370,0];  //6370 km is Earth radius
c=299792.458; //km/s
syms x y z d
eq1=(x-A(1))^2+(y-A(2))^2+(z-A(3))^2==(c*(t(1)-d))^2
eq2=(x-B(1))^2+(y-B(2))^2+(z-B(3))^2==(c*(t(2)-d))^2
eq3=(x-C(1))^2+(y-C(2))^2+(z-C(3))^2==(c*(t(3)-d))^2
eq4=(x-D(1))^2+(y-D(2))^2+(z-D(3))^2==(c*(t(4)-d))^2
[solx, soly, solz, sold] = vpasolve([eq1 eq2 eq3 eq4],[x y,z,d],Guess)
```

(x,y,z,d)=(−41.772709,−16.789194,6370.059559,−0.003201)

(x,y,z,d)=(−39.747837,−134.274144,−9413.624553,0.0185173).

We can solve using MATLAB symbolic solver

Two solutions but z=6370 is valid on earth surface

Solving the GPS Equations (gmu.edu)

Solving GPS Equations for ANKARA

```
A=[17858419.69    -14112320.58  13266513.49];
B=[1-9966634.52323229994.38   7198261.237];
C=[26175407.21    -5560362.718  -87234.876];
D=[6675782.428    -14640726.59  21095927.78];
t=[0.068187931 0.074077043 0.068731306 0.071653924];
Guess=[0,0,0,0];
c=299792458;
syms x y z d
eq1=(x-A(1))^2+(y-A(2))^2+(z-A(3))^2==(c*(t(1)-d))^2
eq2=(x-B(1))^2+(y-B(2))^2+(z-B(3))^2==(c*(t(2)-d))^2
eq3=(x-C(1))^2+(y-C(2))^2+(z-C(3))^2==(c*(t(3)-d))^2
eq4=(x-D(1))^2+(y-D(2))^2+(z-D(3))^2==(c*(t(4)-d))^2
[solx, soly, solz, sold] = vpasolve([eq1 eq2 eq3 eq4],[x y,z,d],Guess)
R1=sqrt(solx(1)^2+soly(1)^2+solz(1)^2)
R2=sqrt(solx(2)^2+soly(2)^2+solz(2)^2)
```

Solving GPS Equations for ANKARA

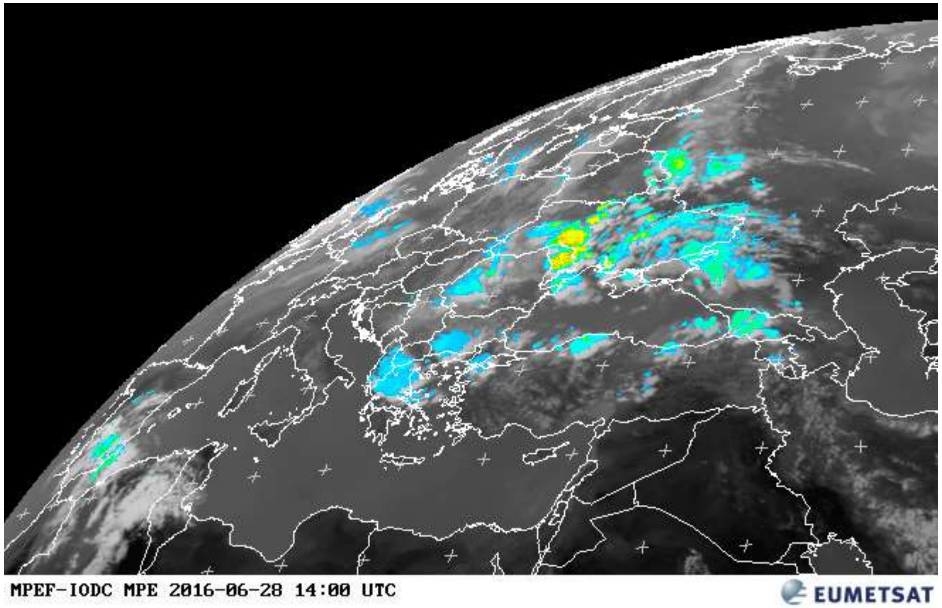
sold =
-0.00999999955081782729264208474529997
0.44806463872710454419382298727737

R1 =6720662.94401188246753478198314 31 (this is true 6720km on Earth)
R2 =99168397.789610515826103874516482

[Principles of the Global Positioning System, solution 1 (mit.edu)]

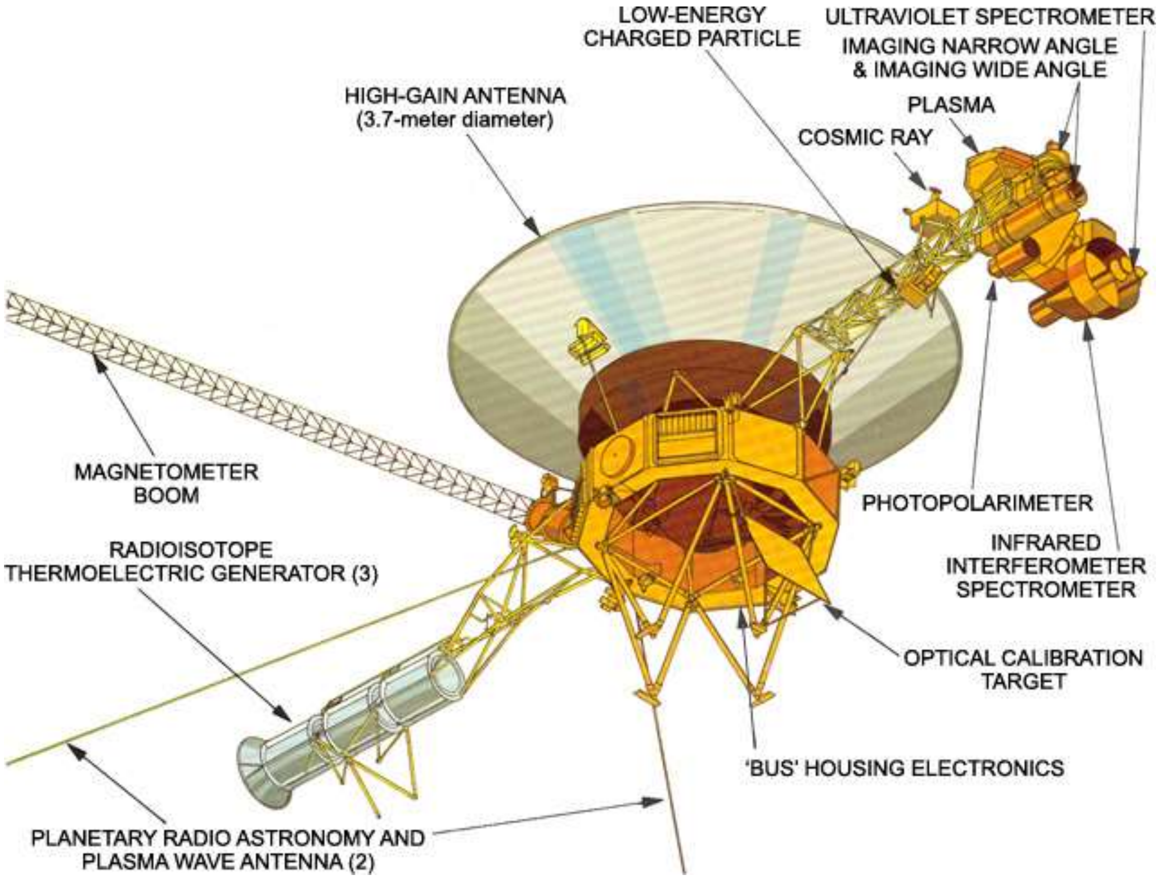
Meteorology Satellites

- EUMETSAT is an intergovernmental organization and was founded in 1986. Our purpose is to supply weather and climate-related satellite data, images and products – 24 hours a day, 365 days a year – to the National Meteorological Services of our Member and Cooperating States in Europe, and other users worldwide.



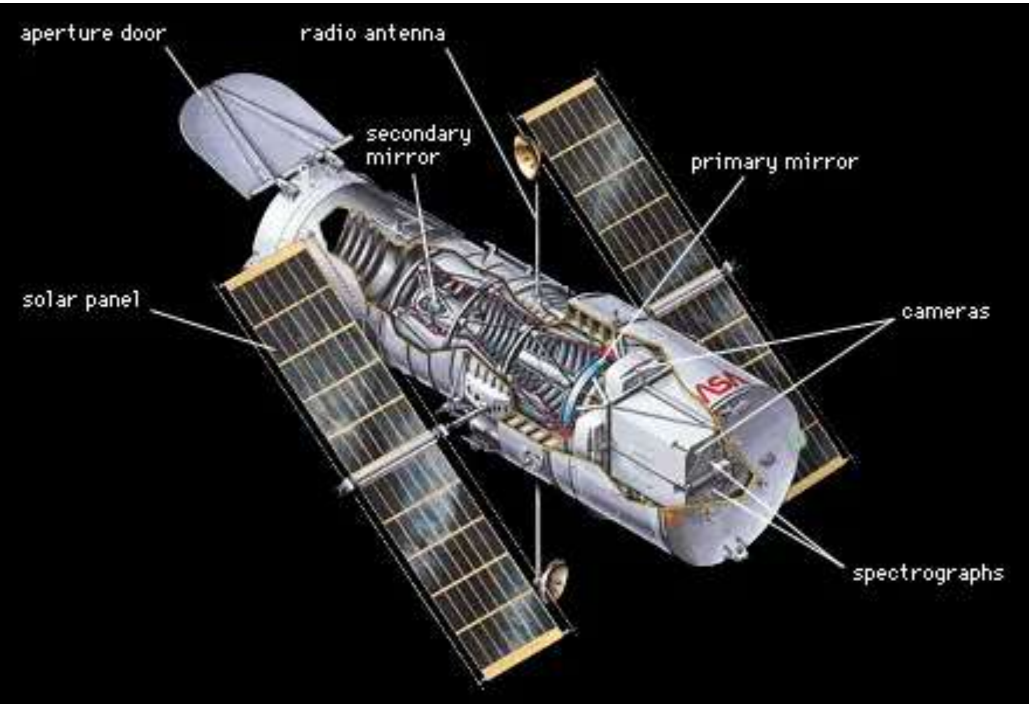
Scientific Satellites

- There are many scientific satellites for deep space exploration Voyager-1 launched 1977

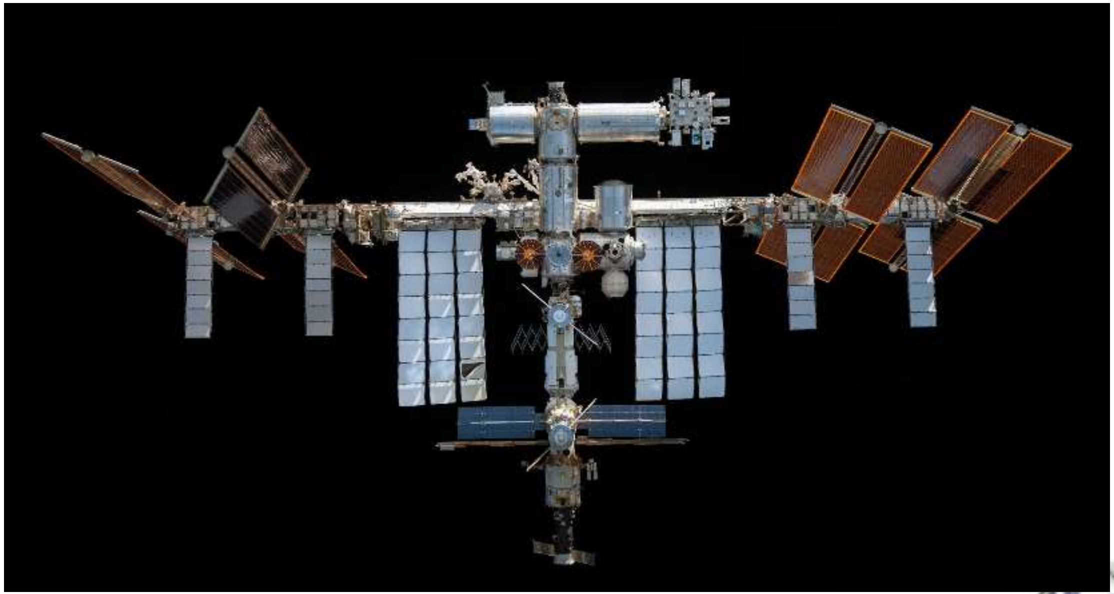


Scientific Satellites

- The Hubble Space Telescope is a space telescope that was launched into low Earth orbit in 1990 and remains in operation



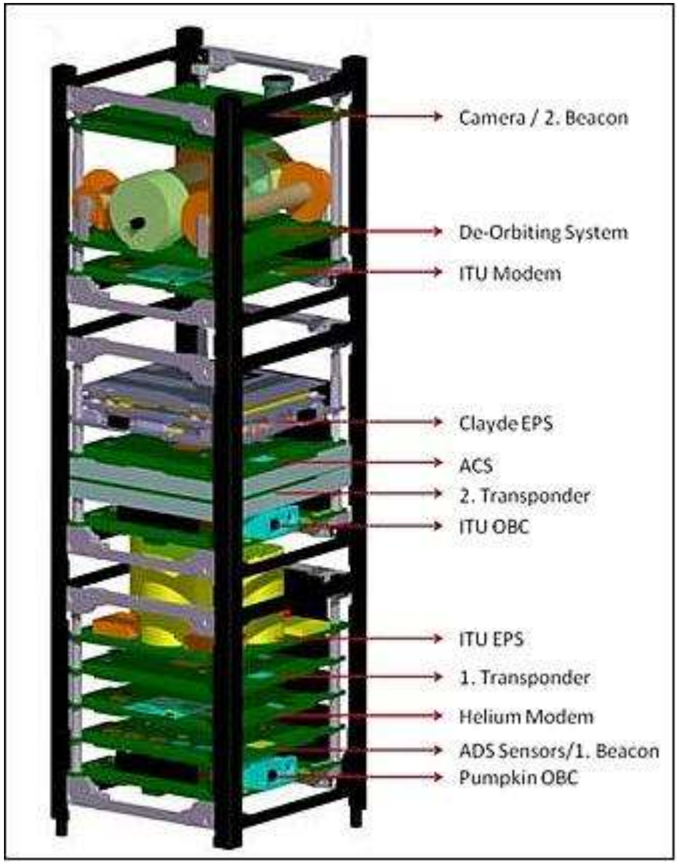
Scientific Satellites

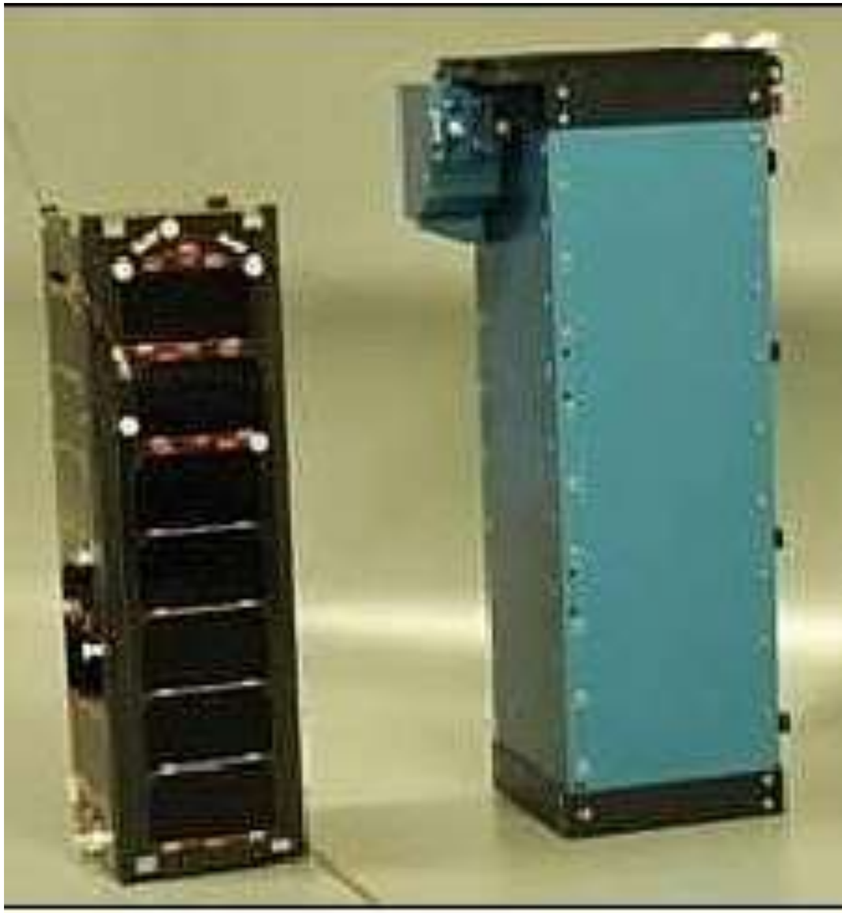


- Five partner agencies, the Canadian Space Agency, the European Space Agency, the Japan Aerospace Exploration Agency, the National Aeronautics and Space Administration, and the State Space Corporation “Roscosmos”, operate the International Space Station, with each partner responsible for managing and controlling the hardware it provides.

CubeSat

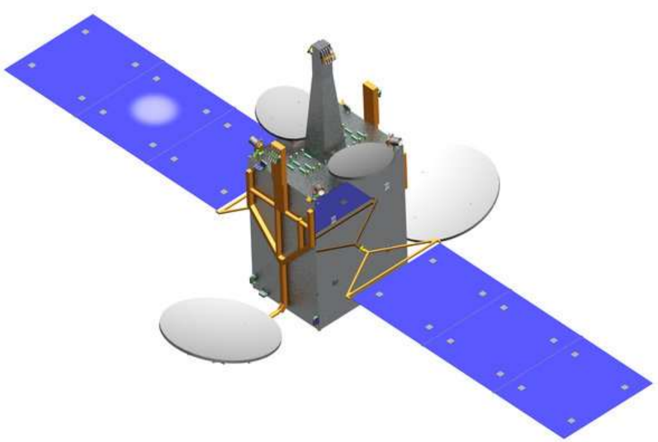
- The CubeSat standard was created by California Polytechnic State University, San Luis Obispo and Stanford University's Space Systems Development Lab in 1999 to facilitate access to space for university students





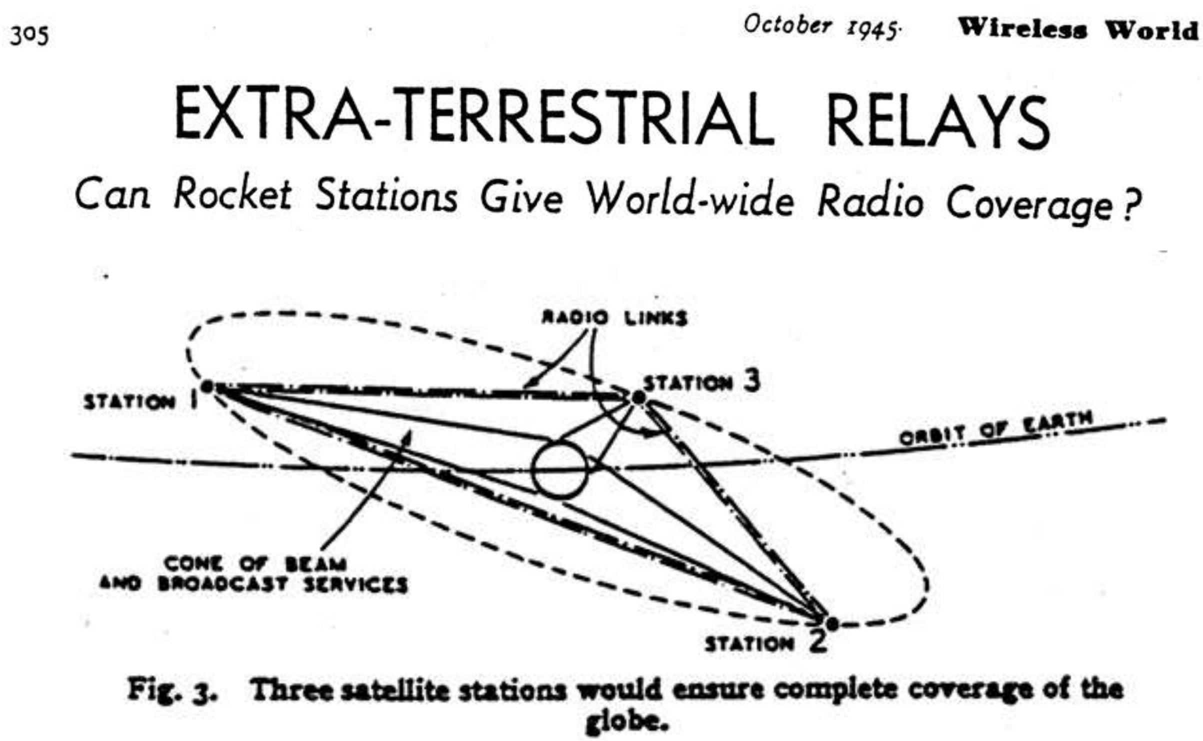
Communication Satellites

- Idea of communication satellites (Extra-Terrestial Relays) was announced by Arthur Clarke in 1945
- The first communication satellite Syncom-2 launched in 1963 (Syncom-1 was in failure)
- Communication satellites benefit from their orbital advantage. One satellite can provide communication, TV Broadcasting to 1/3 of the Earth



Communication Satellites

- Idea of communication satellites (Extra-Terrestial Relays) was announced by Arthur Clarke in 1945



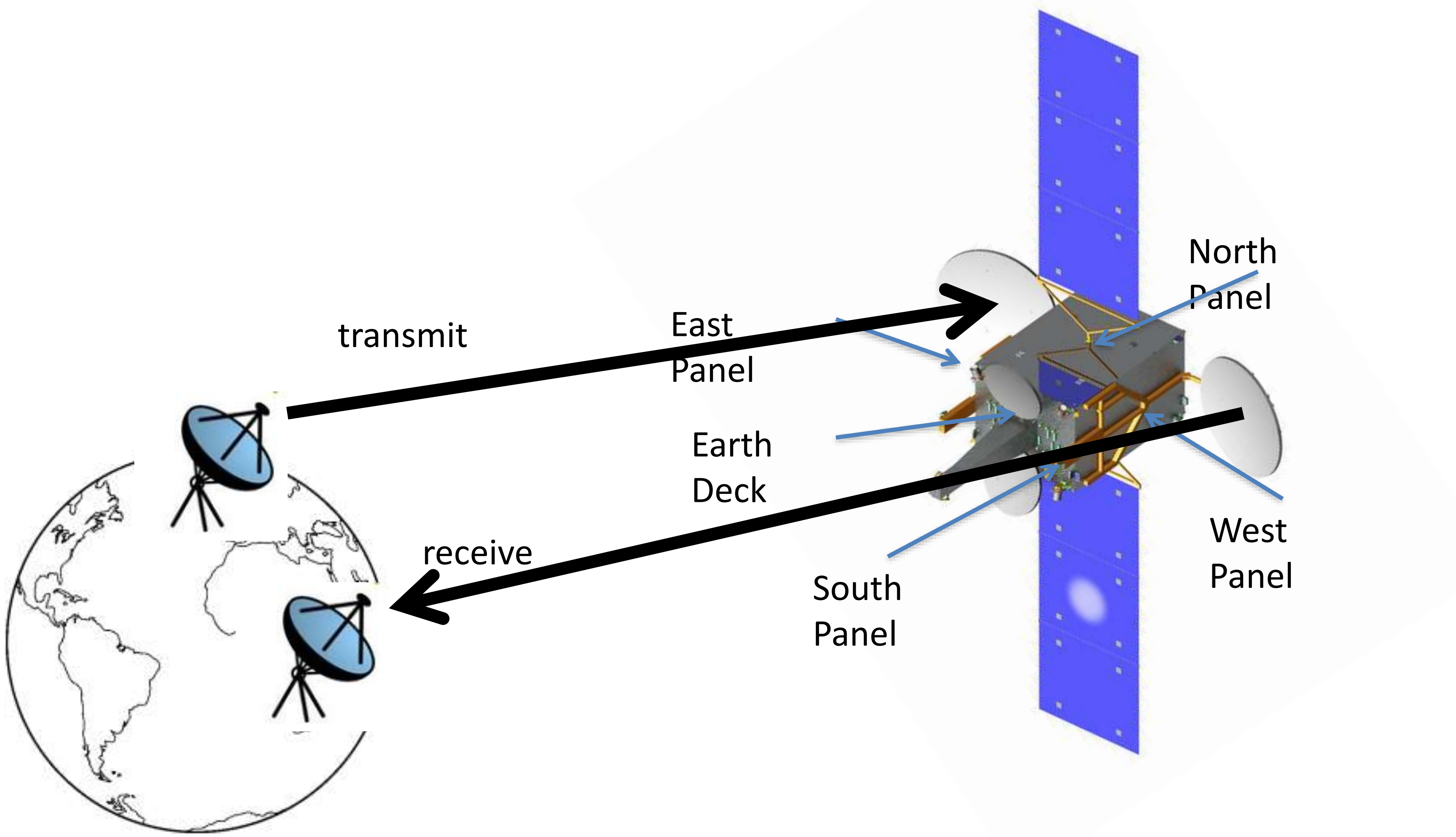
305 October 1945 **Wireless World**

EXTRA-TERRESTRIAL RELAYS

Can Rocket Stations Give World-wide Radio Coverage?

Fig. 3. Three satellite stations would ensure complete coverage of the globe.

Communication Satellites

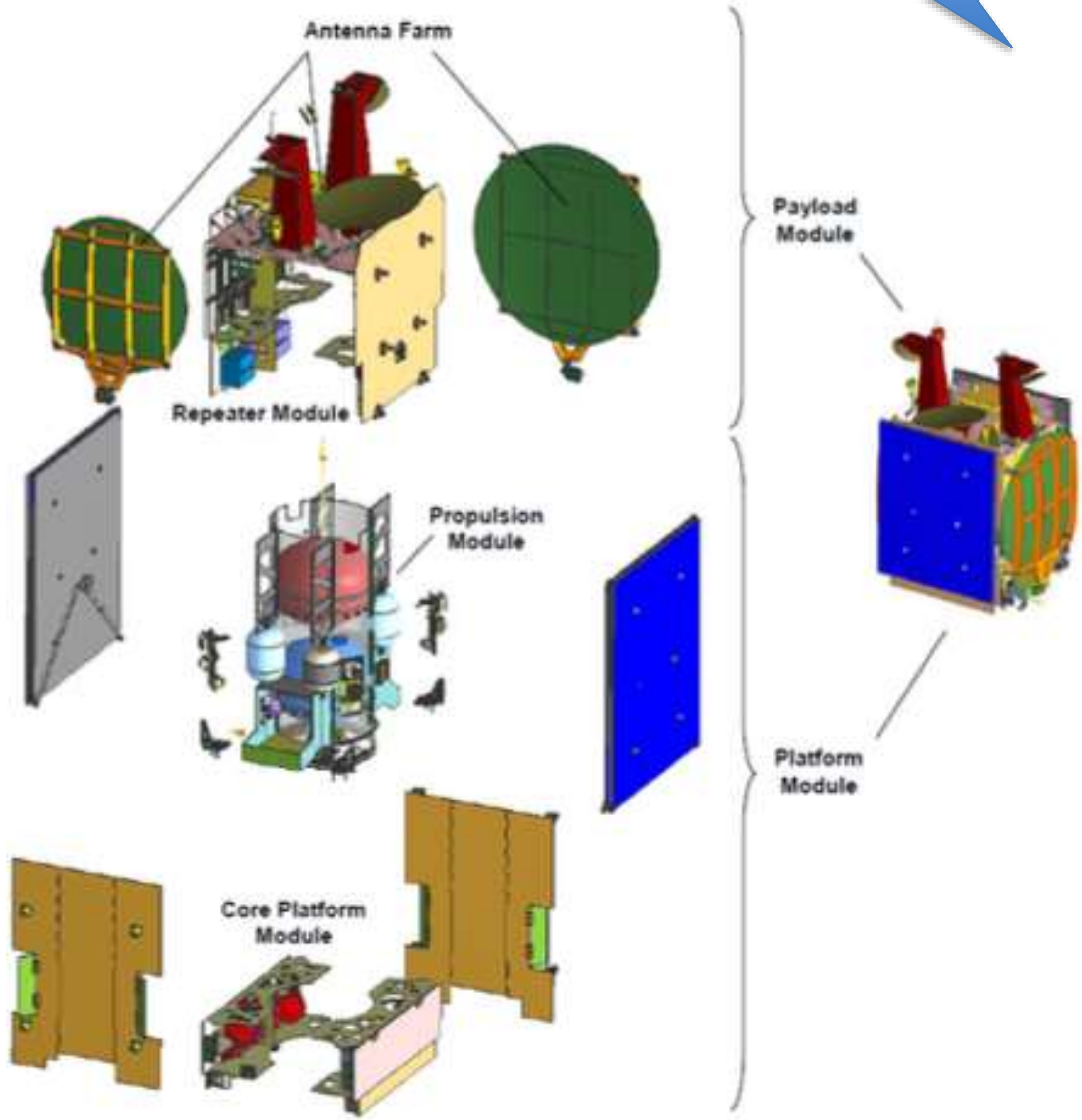


Communication Satellites

Communication satellites consist of two main modules:

1. Platform

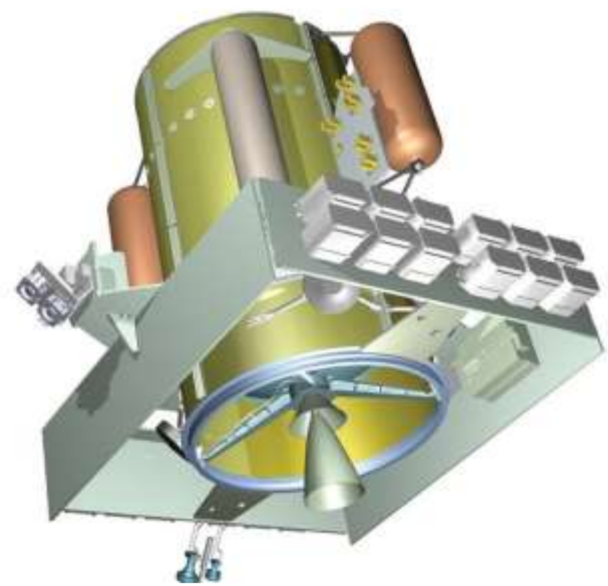
2. Payload



Communication Satellites Platform

Mission of the platform module is to keep the satellite in orbit. Platform Module Subsystems

1. Electrical Power Supply
2. Propulsion
3. Attitude and Orbit Control
4. Telemetry, Command and Ranging
5. Thermal Control
6. Structure

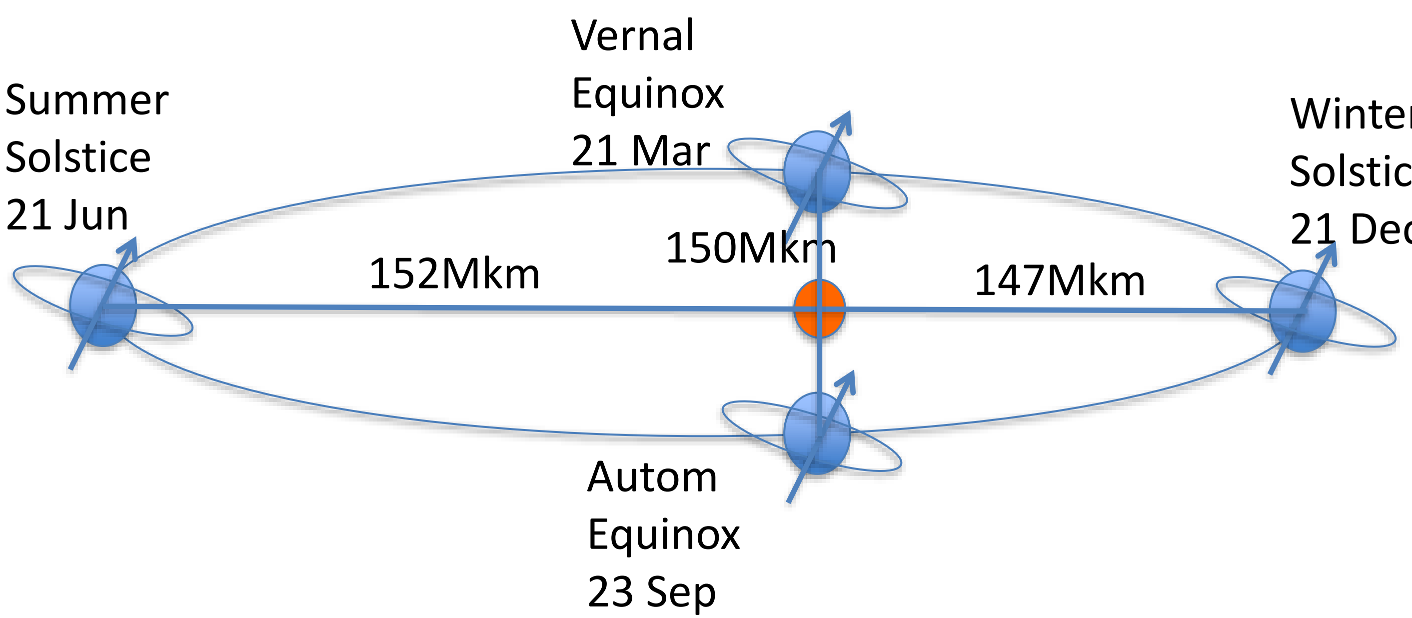


Communication Satellites Platform-Electrical Power Supply

Satellite electrical power is supplied by solar panels. Two type of solar panels are used: Si, GaAs. Li-Ion batteries provides power during **eclipse**. Power conditioning and distribution electronics to provide DC to equipment.

Platform-Solar Flux

- **Solar flux** is inversely proportional to the distance of Earth to Sun.
- Solar flux is minimum **1326 W/m2 at Summer Solstice**.
- There is **23.44° between equatorial plane and sun ecliptic plane**.
- Sun flux has **23.44°** at **Solstices**, perpendicular at Equinoxes
- Satellite stays in shadow (eclipse) during Equinoxes, maximum 72 minutes

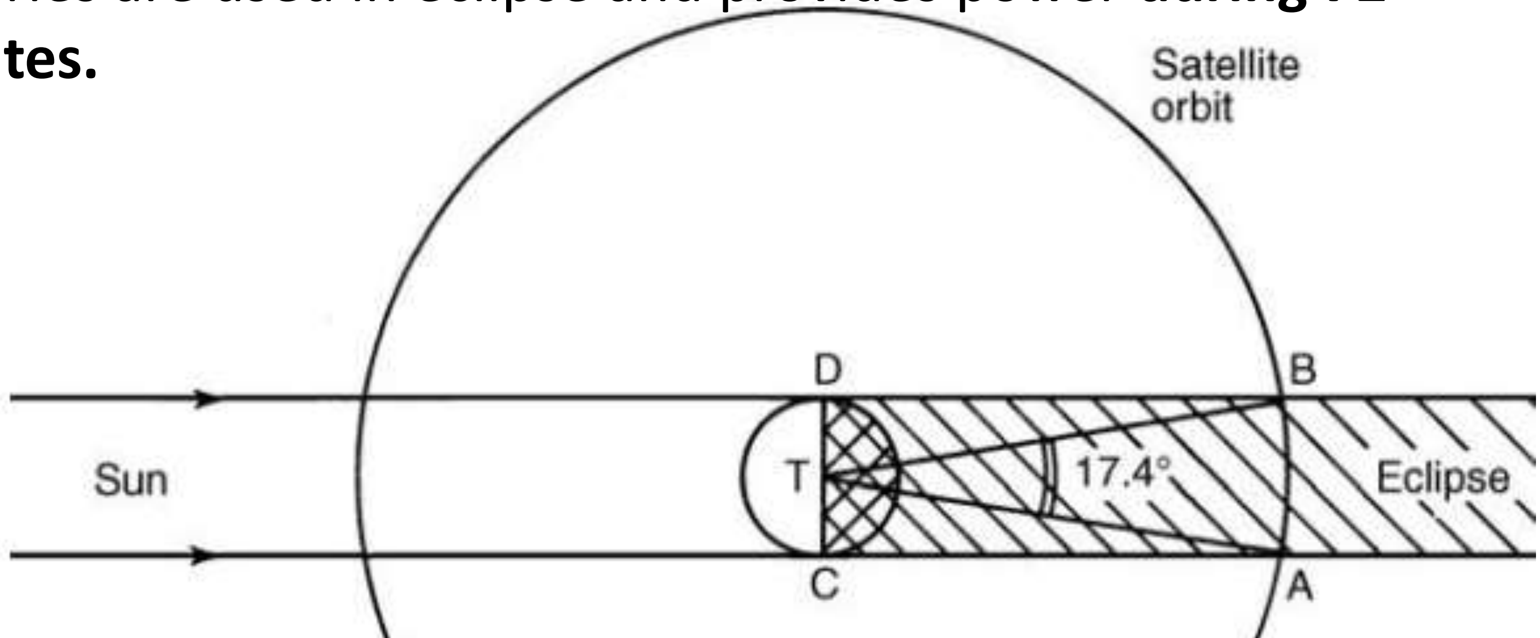


Electrical Power Supply

- Solar flux is maximum in equinox and minimum at solstices due to 23.44° between equatorial and ecliptic planes.
- Batteries are used in eclipse and provides power **during 72 minutes.**
- Batteries are packaged in series and parallel cells.
- Numbers of series cells is related to Bus voltage.
- Number of parallel cells is calculated for power requirements.

Electrical Power Supply

- Batteries are used in eclipse and provides power **during 72 minutes.**



$$\tan(\theta) = \frac{6378}{42164}$$

$$\theta = 8.6°$$

$$Te = 24 \times 60 \times \frac{2\theta}{360}$$

$$Te = 69 \min + \ penumbra = 72 mins$$

Communication Satellites Platform-Solar Power

Si solar cells has efficiency of 17%. 15 years degradation of Si cells is 16%. Calculate the solar panel area required for 7kW. Assume 20% losses (cabling, filling factor etc).

$$\boldsymbol{Psat = Psun \times cos(tilt)xEff \times (1 - Degradation) \times (1 - Losses) \times Area}$$

$$\boldsymbol{7000W = 1326W/m2 \times \cos(23.44°) \times 0.17 \times (1 - 0.16) \times \ (1 - 0.2) \times Area}$$

$$\boldsymbol{Area = 50m^2}$$

half of this 25m2

25/3 = 8m2 = 3m x 2.6m

TURKSAT 6A-Solar Power

Si solar cells has efficiency of 17%. 15 years degradation of Si cells is 16%. Calculate the solar panel area required for 7kW. Assume 24% losses (cabling, filling factor etc).

$$\boldsymbol{Psat = Psun \times cos(tilt)xEff \times (1 - Degradation) \times (1 - Losses) \times Area}$$

$$\boldsymbol{7000W = 1326W/m2 \times \cos(23.44°) \times 0.17 \times (1 - 0.16) \times \ (1 - 0.24) \times Area}$$

$$\boldsymbol{Area = 50m^2}$$

half of this 25m2

25/3 = 8m2 = 3m x 2.6m

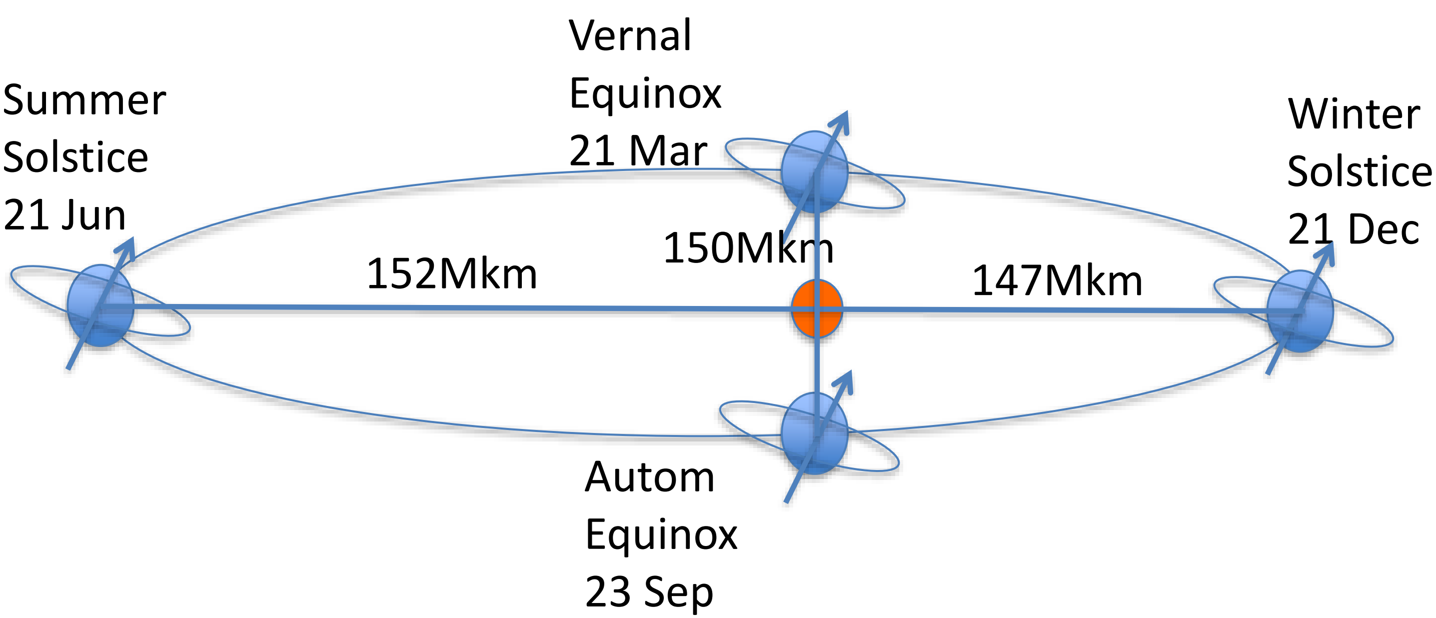
Communication Satellites Platform-Solar Power

Table 10.5 Typical characteristics of solar cell technologies

Cell type	Efficiency, BOL 28 °C		Efficiency, EOL 1E15, 60 °C		Cell weight (kg/m^2)
	%	KW/m^2	%	KW/m^2	
Si (200 μm)	12.6	0.170	8.7	0.118	0.464
Si (67 μm)	15.0	0.203	9.2	0.124	0.156
Si (100 μm) with diode	17.3	0.234	12.5	0.169	0.230
GaAs/Ge (137 μm)	19.6	0.265	14.7	0.199	0.720
DJ cascade (137 μm)	21.8	0.295	18.1	0.245	0.720
TJ standard (140 μm)	26.0	0.352	21.0	0.284	0.840
TJ improved (140 μm)	29.9	0.393	25.1	0.340	0.840
Thin film	12.6	0.170	9.5	0.128	0.100

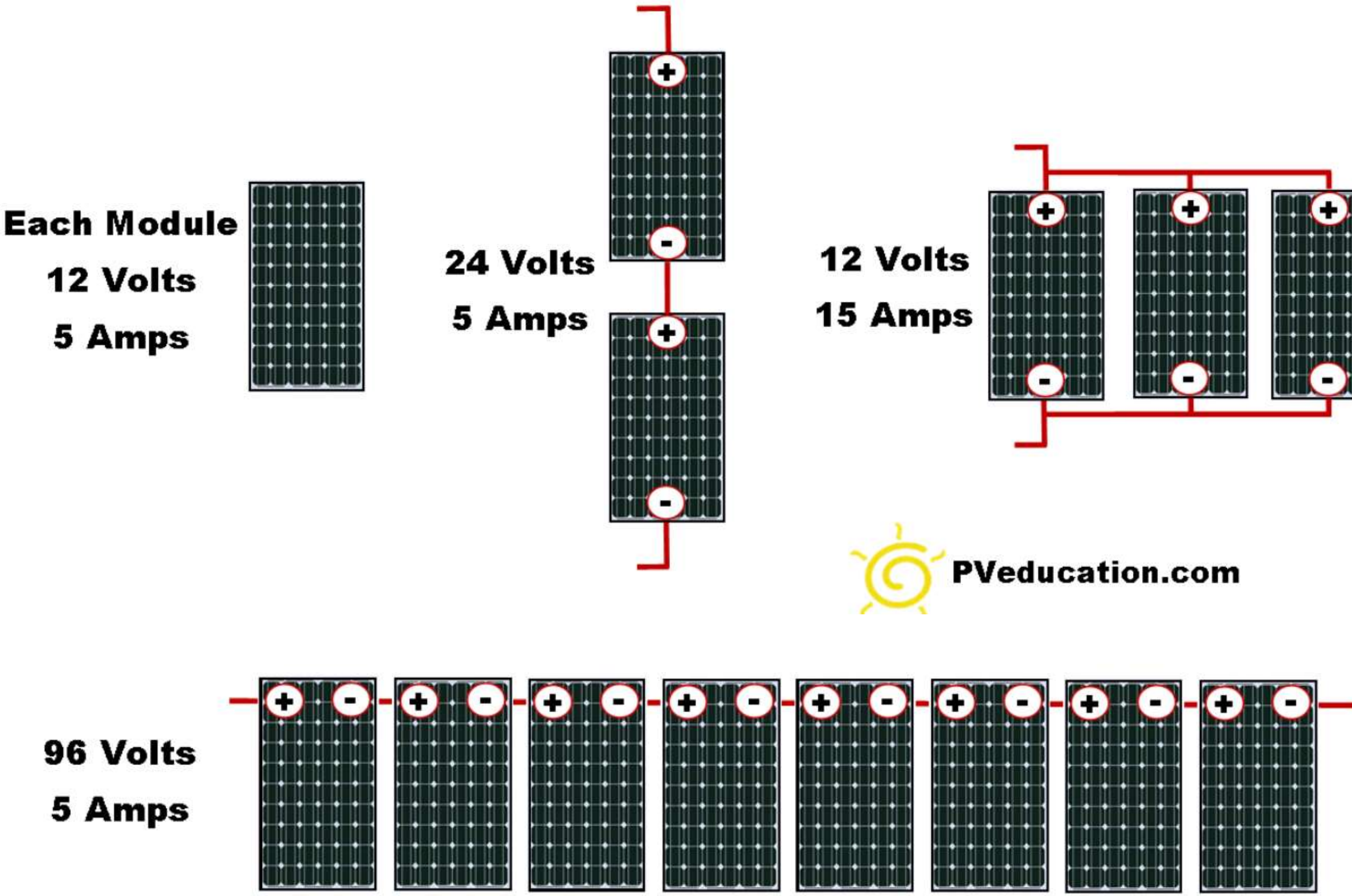
Communication Satellites Platform-Batteries

- Satellite batteries are Li-Ion and used during eclipse seasons of the satellite where the satellite stays in shadow of Earth
- Battery cells are in serial and parallel connection



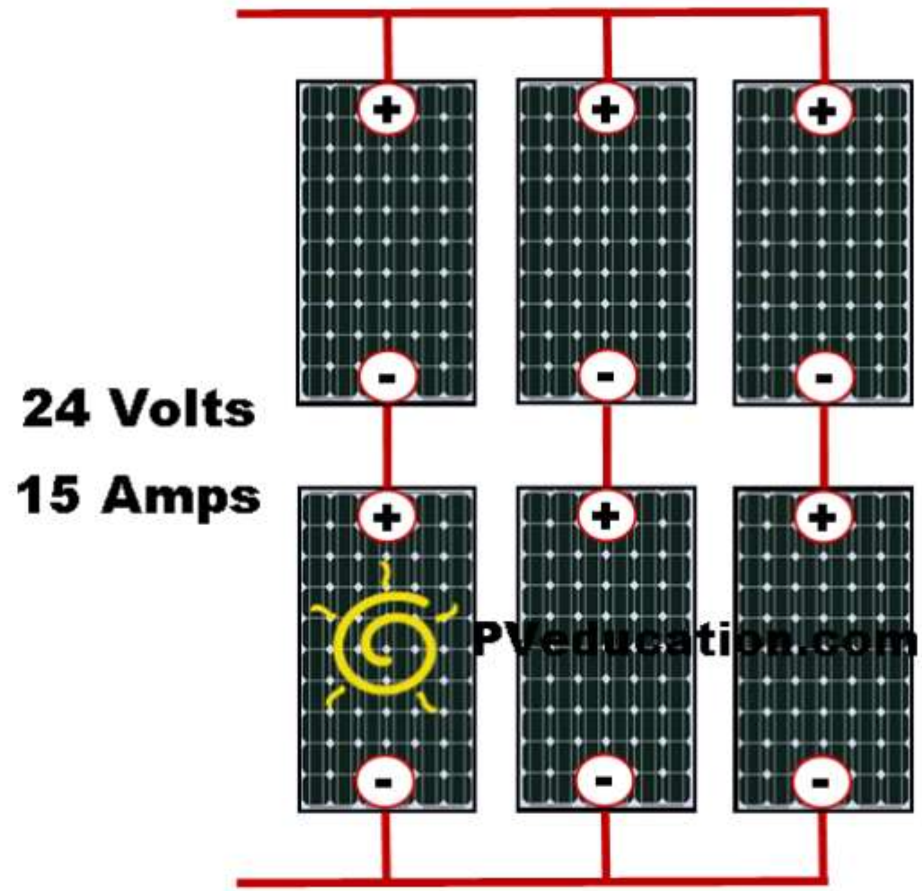
Series and Parallel Wiring

The following image is a great example of series and parallel wiring.



Series Parallel Combination:

Here is an example of what is found in most large solar systems, a series and parallel wiring combination.



Satellite Battery Sizing

Example: A battery cell is 4 Volt and 140Wh, Required satellite power is 7kW. What is the number of serial and parallel cells , Vbus=96V? 72 minutes eclipse duration.

$$\boldsymbol{Psat = 7000W, Peclipse = 7000 \times \frac{72}{60} = 8400\, Wh\, required}$$

$$\boldsymbol{Vbus = 96V, \frac{96}{4} = 24\ serial\ cell}$$

$$\boldsymbol{1\ cell\ is\ 140\ Wh}$$

$$\boldsymbol{24s = 24 \times 140 = 3360Wh\ not\ enough}$$

$$\boldsymbol{24s2p = 24 \times 2 \times 140 = 6720\ Wh\ not\ enough}$$

$$\boldsymbol{24s3p = 24 \times 3 \times 140 = 10080\ Wh\ \text{is enough}}$$

So battery architecture is 24 serial 3 parallel cell is enough 24S3P

Satellite Battery Sizing

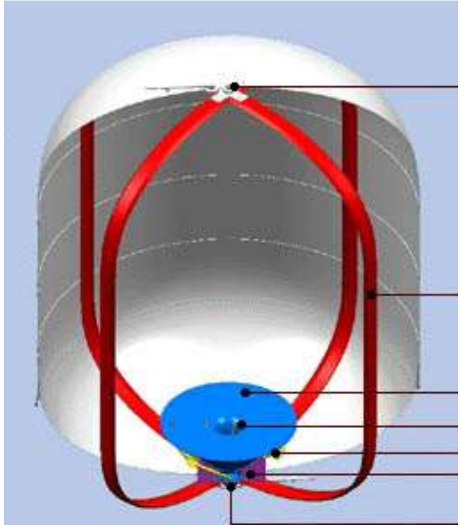
Table 10.6 Characteristics of battery cells

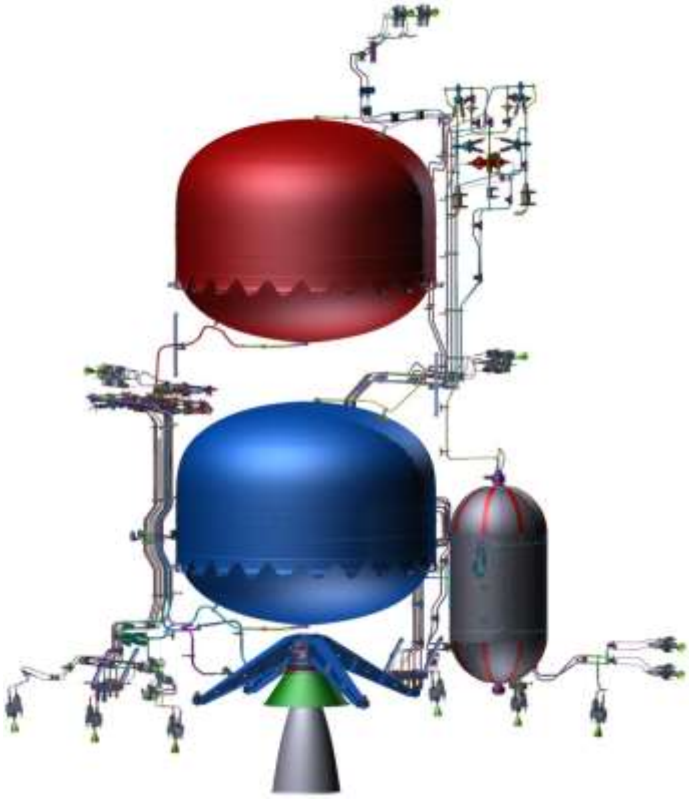
Type of cell	Electrolyte	Nominal cell voltage (V)	Energy density (W h/kg)	Temperature range (°C)	Cycle life at levels of depth of discharge 25%	50%	75%
NiCd	KOH solution	1.25	25–30	−10 to +40	20 000	3 000	800
NiH_2	KOH solution	1.30	50–70	−10 to +40	15 000	>2 000	1 000
Li-ion	Non-aqueous	3.6	120–175	0 to +40	>60 000	>10 000	>1500
AgCd	KOH solution	1.10	60–70	0 to +40	3 500	750	100
AgZn	KOH solution	1.50	120–130	+10 to +40	2 000	400	75
Pb–Acid	Diluted sulphuric acid	2.10	30–35	+10 to +40	1 000	700	250

Communication Satellites Platform-Propulsion

Propulsion system brings the satellite to GEO orbit using apogee motors and keep the satellite in orbit using thrusters.

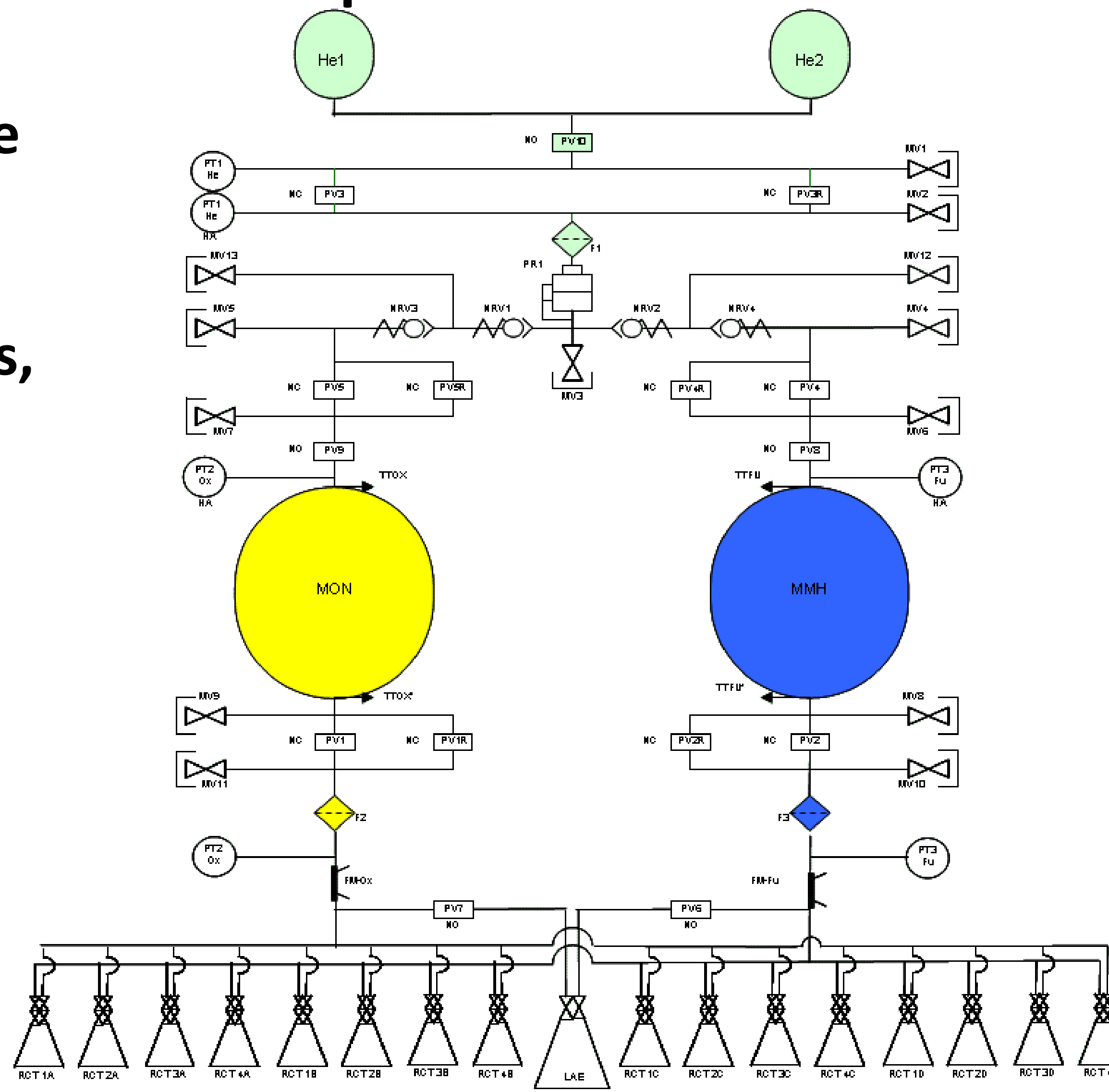
Bi-chemical (MMH+MON) and electrical propulsion systems are used in communication satellites.





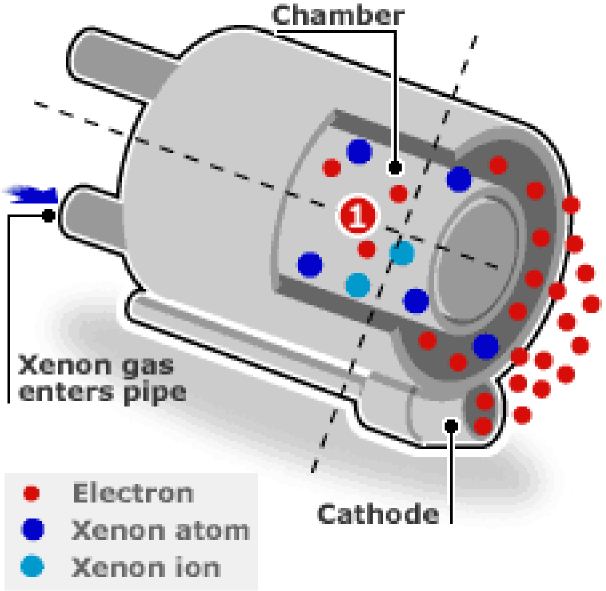
Communication Satellites Platform-Propulsion

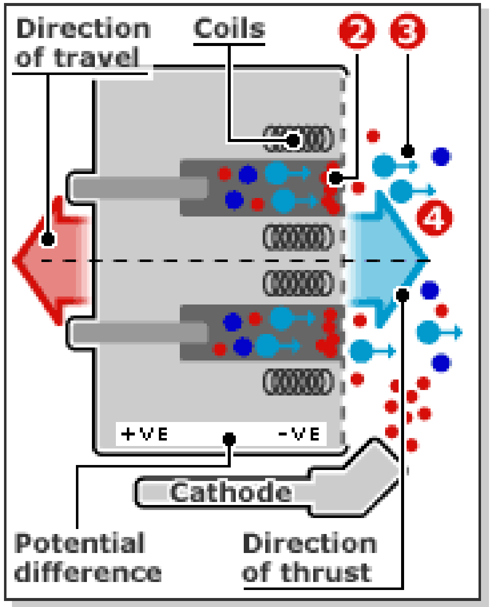
- Helium tanks pressurize the propellant
- Pyro-valves, pressure regulators, check valves, filters
- MMH: Monomethylhydrazine
- MON: mixed oxides of nitrogen
- Apogee motor: 400N
- Thrusters 10N



Communication Satellites Platform-Electrical Propulsion

- Electric thrusters (Hall effect and Ion) uses Xenon gas. Due to their high specific impulses (Hall ISP=1500s) they are more efficient compare to chemical thrusters (ISP=300s). This allows more space for payload or extended lifetime of the satellite



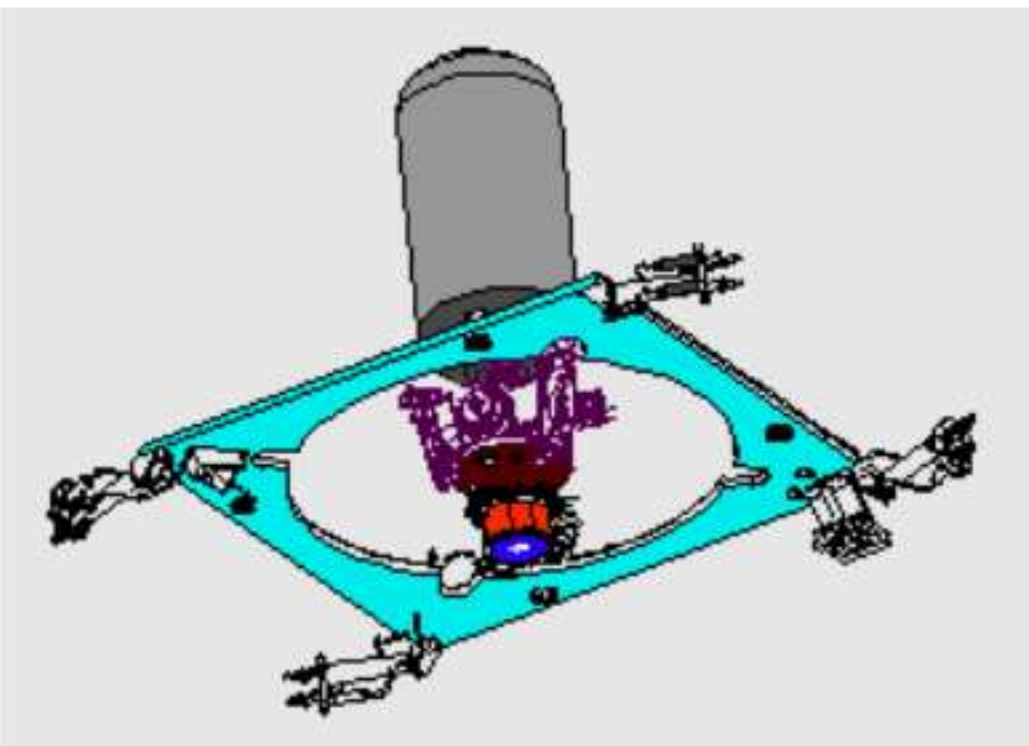


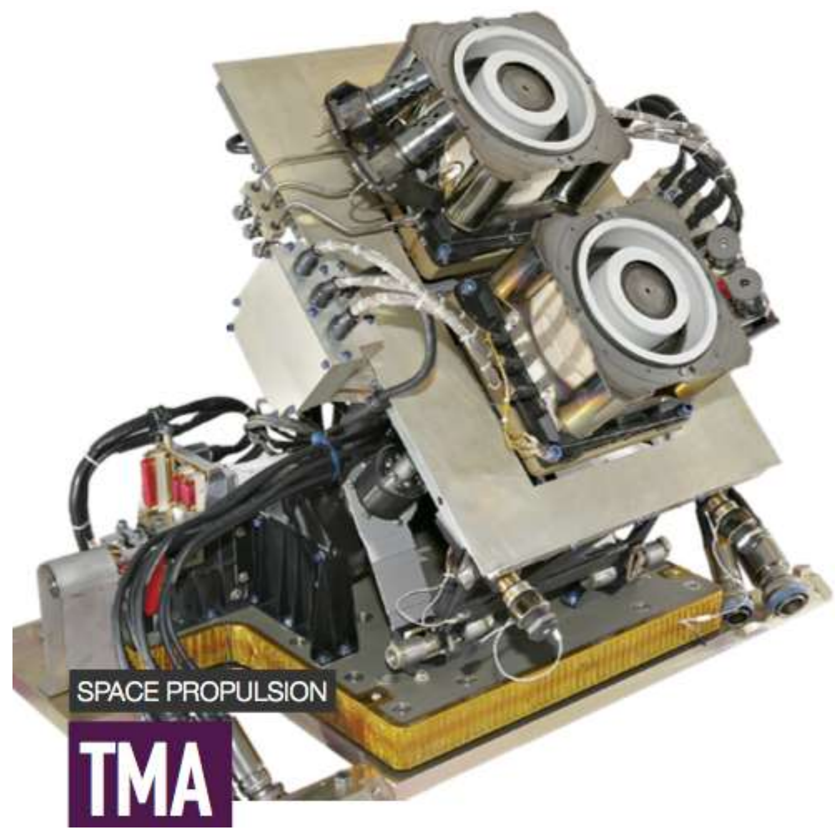
Communication Satellites Platform-Electrical Propulsion

- **Turkey’s first Hall Effect Propulsion system with all necessary equipment was also designed, manufactured and tested in the scope of this project. The first prototype of the 1.5 kW Hall Effect thruster was designed, manufactured and tested in 2015 using the established infrastructure. The other parts comprising the electric propulsion system – Xenon Feeding Unit, Cathode, Power Processing and Control Units - were also designed, manufactured and successfully tested in the scope of HALE. This developed system, being Turkey’s first indigenous electric propulsion system, will be experimentally used on TÜRKSAT 6A satellite and gain flight heritage.**

Communication Satellites Platform-Electrical Propulsion

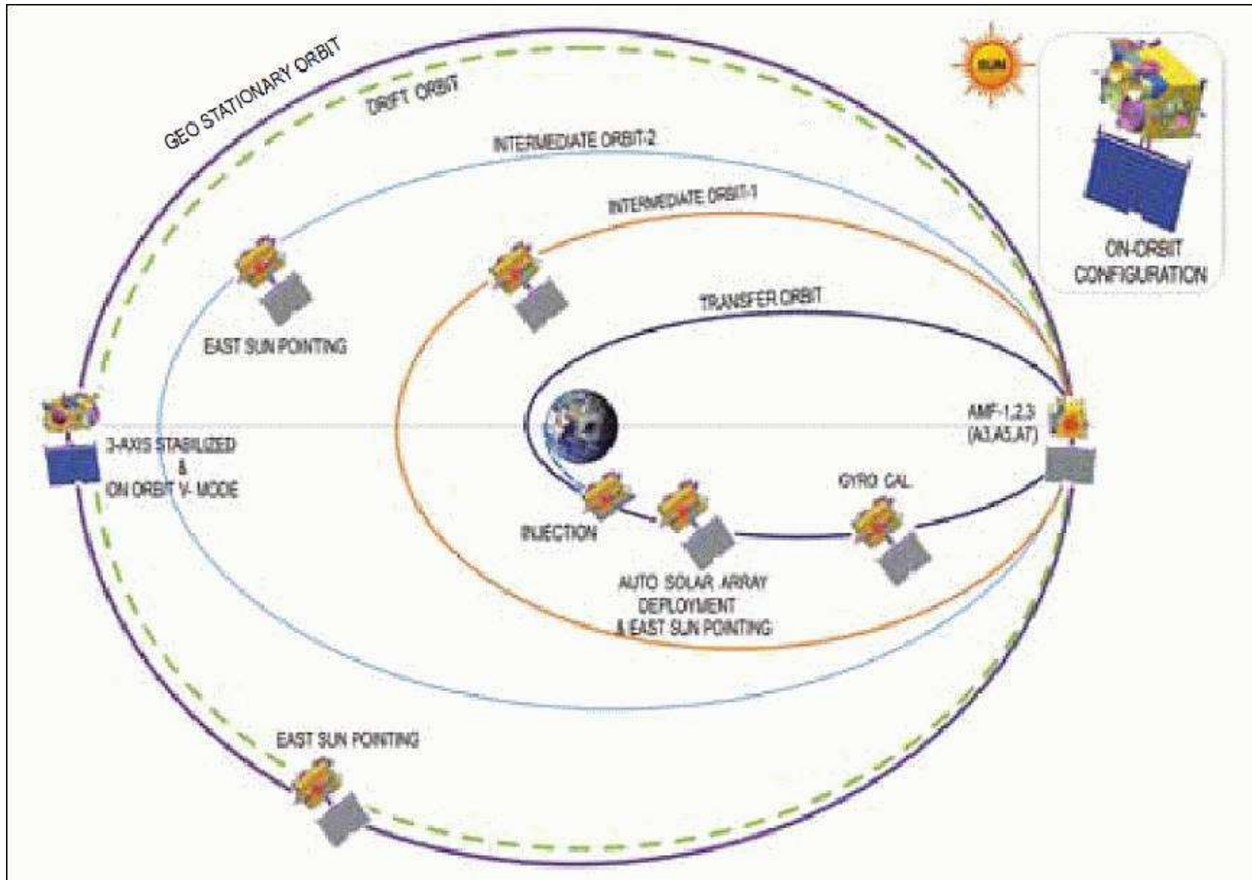
- **Electric thrusters has two axis steering mechanism for performance optimization**





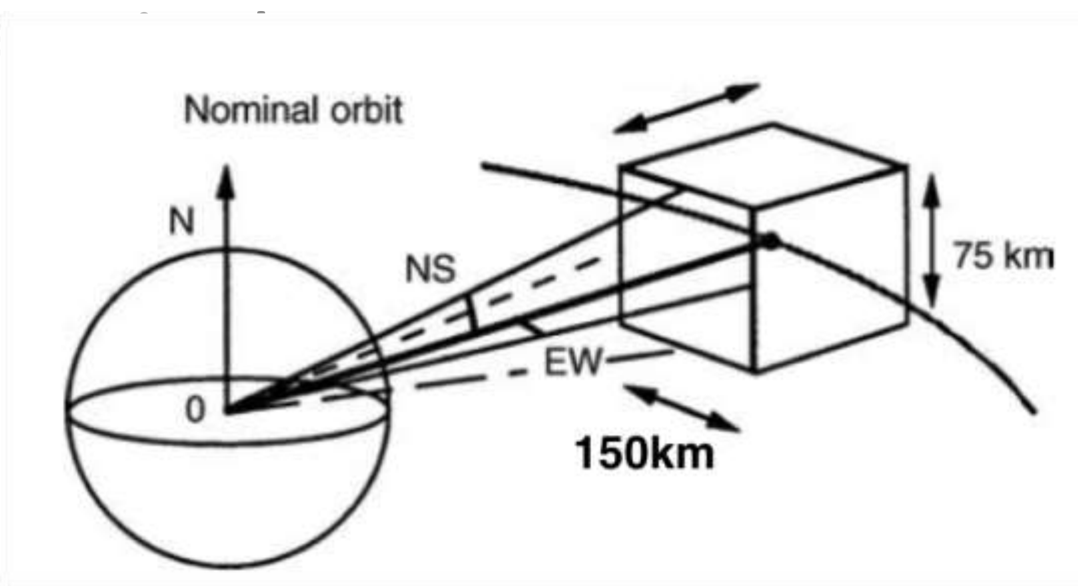
Communication Satellites Platform-Propulsion System

- **Satellites are left in GTO orbit after separation from the launcher.**
- **Satellites raises their orbit to GEO using apogee motors**



Communication Satellites Platform-Propulsion System

- **Geostationary satellites has to be kept inside a ±0.1° longitude box due to (Internation Telecommunication Union) ITU regulations. Operators keeps inclination within ±0.05°**
- **Geostationary orbit is 42164km from the Earth center. ±0.1° is 150km approximately.**
- **Station keeping is performed East-West and North-South maneuve**



Communication Satellites Rocket Equation

- **Propellant defines the lifetime of the satellite.**
- **Satellites can not keep their orbital position without propellant.**

$$\Delta \boldsymbol{M} = \boldsymbol{M}\left(\mathbf{1} - \boldsymbol{e}^{\frac{-\Delta \boldsymbol{V}}{(\boldsymbol{go.Isp.eff})}}\right)$$

M: satellite mass before the maneuver
Isp: specific impulse
eff: efficiency of thruster

The specific impulse is the impulse force x time communicated during a time dt by unit weight of propellant consumed during this time interval.

Communication Satellites Rocket Equation Example-1

- **Satellites spend most of their fuel during orbit raising phase. They utilize 400N apogee motor after separation from rocket to go to GEO orbit.**
- **A 3000kg satellite needs 1494 m/s delta V for orbit raising. How much fuel required ? Isp=321 sec, efficiency=0.99. Satellite initial propellant is 1700 kg.**

DM = M*(1-exp (-DV/(go*Isp*eff)))

DM = 3000*(1-exp(-1494/(9,80665*321*0.99))

DM= 1142.5kg change in satellite mass (=fuel)

DM/Mfuel=67%

%67 of the total propellant spent at orbit raising!

Communication Satellites Rocket Equation Example-2

- **A 3000kg satellite spent 1142.5kg for orbit raising. 912 m/s delta V is required during 20 years for North South station keeping maneuvers. How much fuel is required for bi-propellant (Isp=286 sec, efficiency=0.92) and electrical propulsion system (Isp=1500 sec, efficiency=0.92)**

$$\Delta M = M(1 - e^{-\Delta V/(go.Isp.eff)})$$

$$\Delta M = (3000 - 1142.5).(1 - e^{-912/(9.80665x286.x0.92)})$$

$$\Delta M = 553kg$$

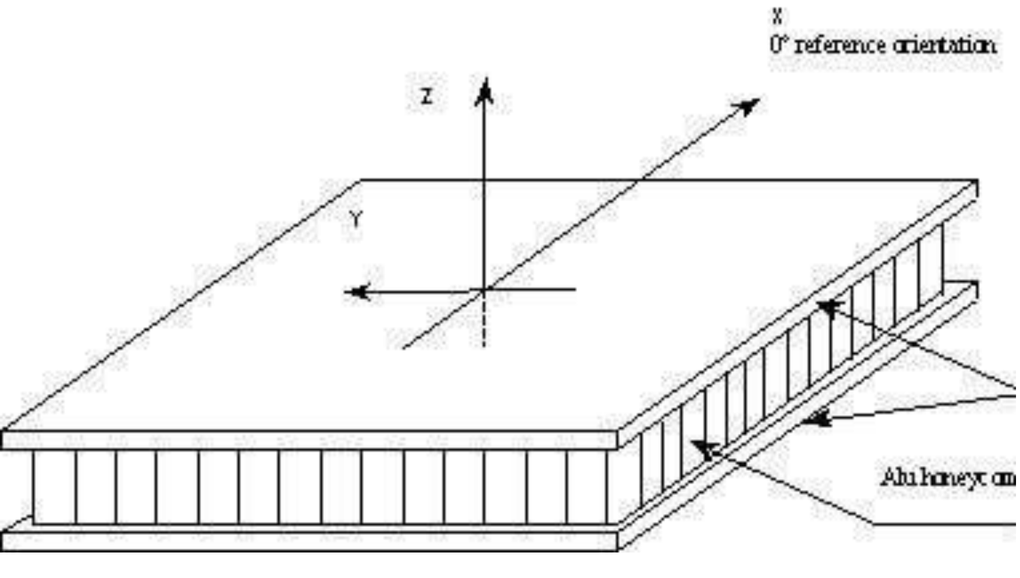
$$\Delta M_{Electrical} = (3000 - 1142.5).(1 - e^{-912/(9.80665x1500.x0.92)})$$

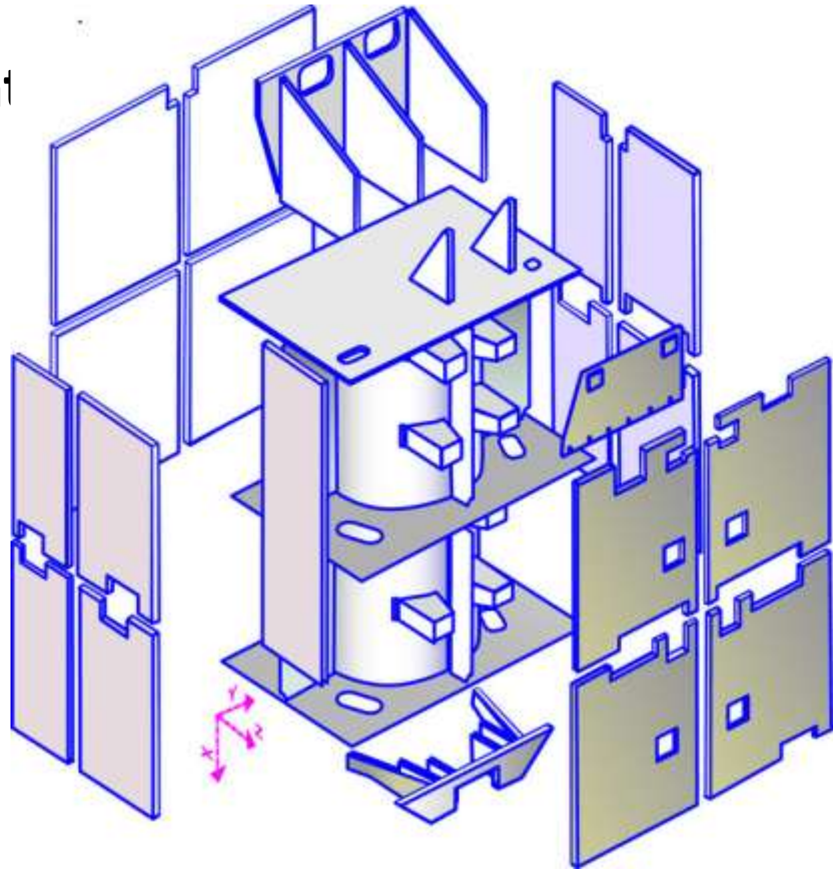
$$\Delta M_{Electrical} = 121.1kg$$

$$\frac{553}{121.1} = 4.6$$

Communication Satellites Platform-Structure

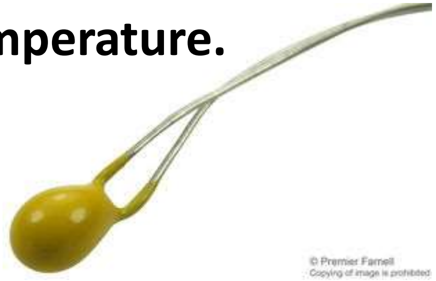
- **Sandwich Panel: Aluminum honeycomb between two carbon fiber/aluminum panels**
- **Central cylinder: There are propellant tanks inside. Launch adapter is connected to central cylinder**





Communication Satellites Platform-Thermal Control

- **Thermal control keeps the satellite internal temperature around 25°C while outside temperature changes between -150 to 150**
- **Optical Solar Reflector (OSR): radiates heat**
- **Heat-pipes: Distributes heat**
- **Tape or film Heaters**
- **Thermistors to measure temperature.**

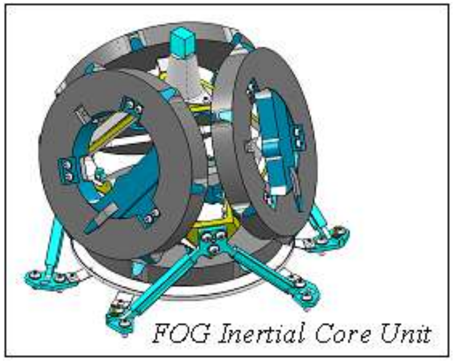


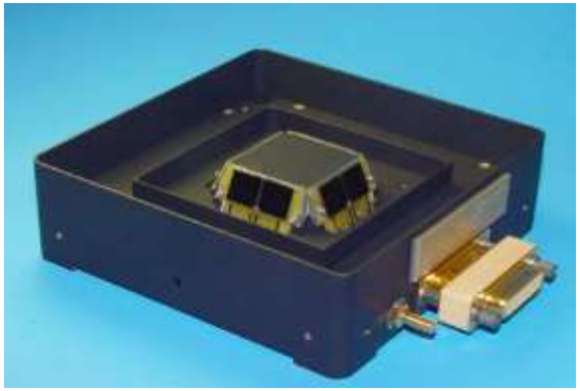
Communication Satellites Platform-Thermal Control

- **MLI Blankets: provides isolation between outside and inside of the satellite. Gold or black MLI's.**
- **Coldest part of the satellite is north and south panels due to sun angle (similar to Earth). Thus, most power dissipating devices (TWTA's) are located on North and South Panels.**
- **Panels outer surface is covered by OSR and MLI's. Required OSR area depends on the heat dissipation.**

Communication Satellites Platform-Attitude and Orbit Control

- **Momentum wheels controls disturbance torques created by solar magnetic and RF pressure torques. When wheel reaches to its maximum speed, unloaded by thrusters.**
- **Sun Sensors measures direction of Sun. 4 solar cell provides current and angle can be calculated using these values.**
- **Gyro: fiber or laser gyros measures acceleration at each axis. Star tracker is used in normal mode Gyro is used in emergency**
- **Star tracker gives looking angle (attitude) of the satellite wrt stars. A star map is loaded and star tracker can calculate its angle using maximum 10 stars.**





Communication Satellites
Platform-Telemetry Command and Ranging

- **Telemetry transmitters send parameters of the satellite equipment to ground control station**
- **Command receivers decodes commands transmitted from ground control station**
- **Ranging is used to measure radial distance of the satellite to the ground control station**

Communication Satellites
Payload

- **Satellite payload receives signals sent from the Earth ground station, changes the frequency, amplifies and re-transmits to Earth.**
- **LNA: Low Noise amplifier receives and amplifies the signals**
- **DOCON: Down converter changes the frequency**
- **IMUX: Input Multiplexer splits signals to channels**
- **Switches: provides redundancy routing**
- **TWTA: Travelling Wave Tube Amplifier is a power amplifier**
- **OMUX: combines signal to route to antenna**

Communication Satellites
Payload Block Diagram

Preliminary Design of TUSAT Satellite Communication Payload

Mesut Gokten, Ahmet F. Yagli, Lokman Kuzu, *Member, IEEE*, Veli Yanikgonul, Erol Sanli, Senol Gulgonul

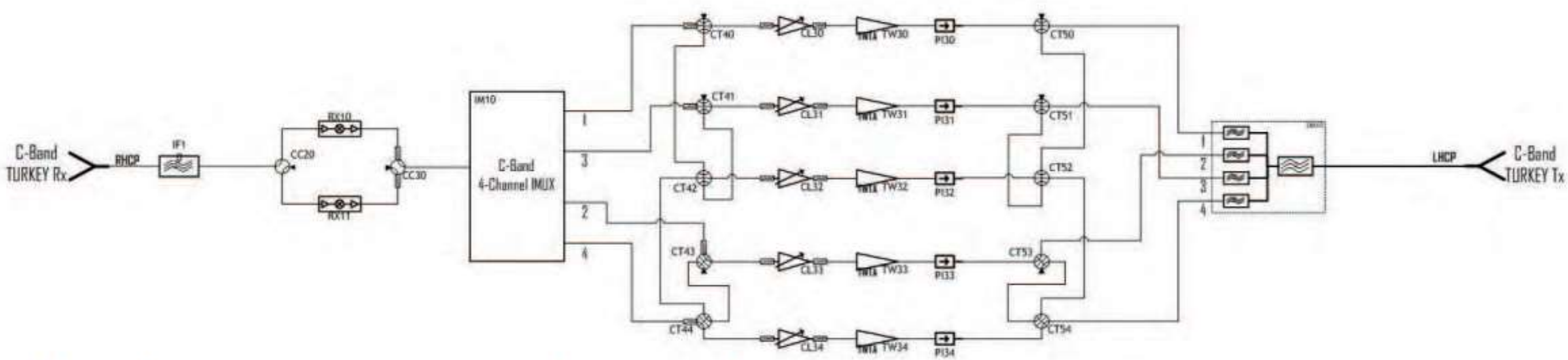
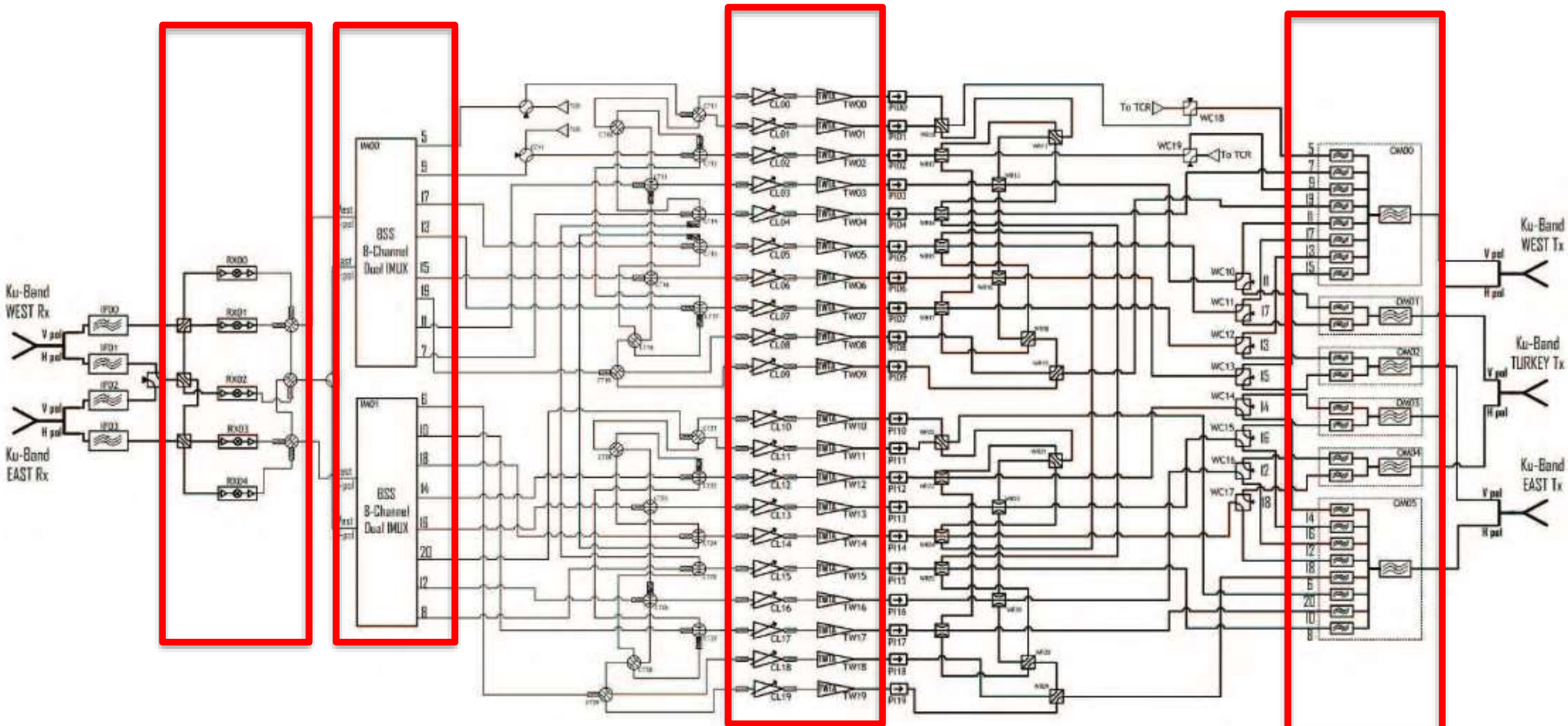


Fig. 3. TUSAT Payload Configuration, Ku-band on the top and C-band on the bottom

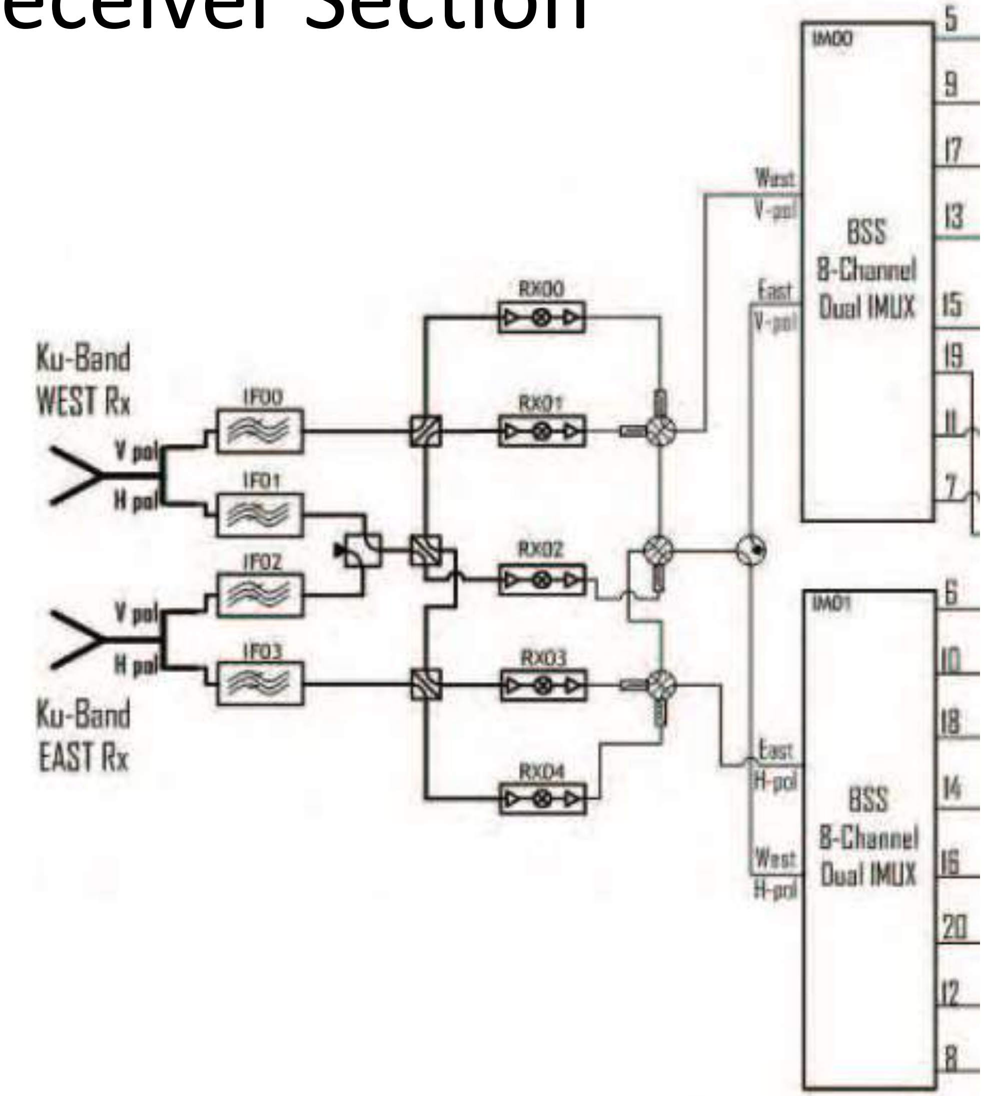
Communication Satellites
Payload Block Diagram

- Real payload diagram is more complex due to number of channels and equipment.



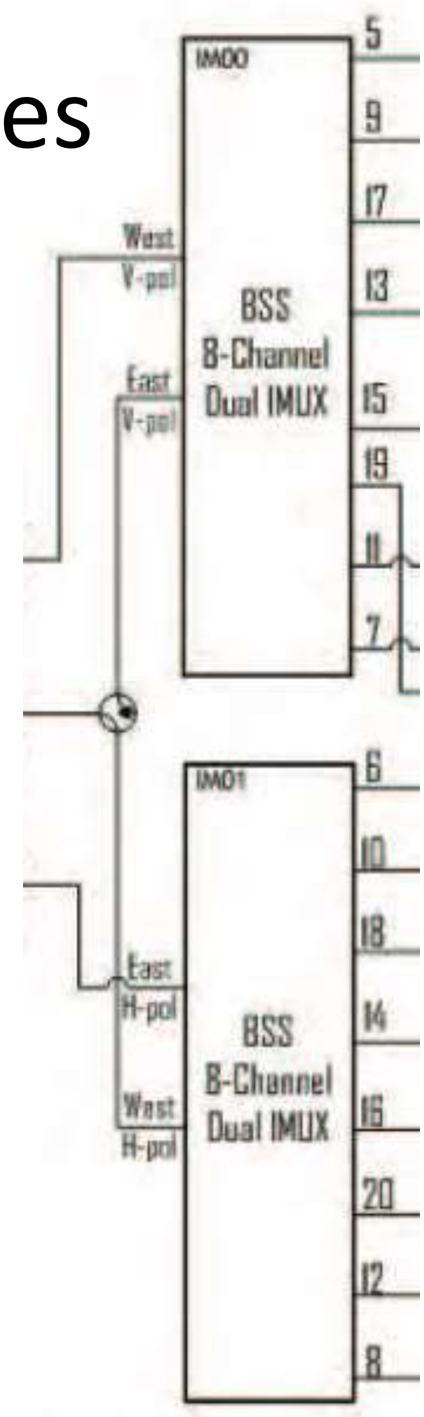
Communication Satellites
Payload: Receiver Section

- Receiver/DOCON has wide filter and amplifies signal received with very low noise (LNA)
- A small redundancy network required. There are 5 receivers but 4 of them actively used.
- Receivers feed IMUX's



Communication Satellites
Payload: IMUX

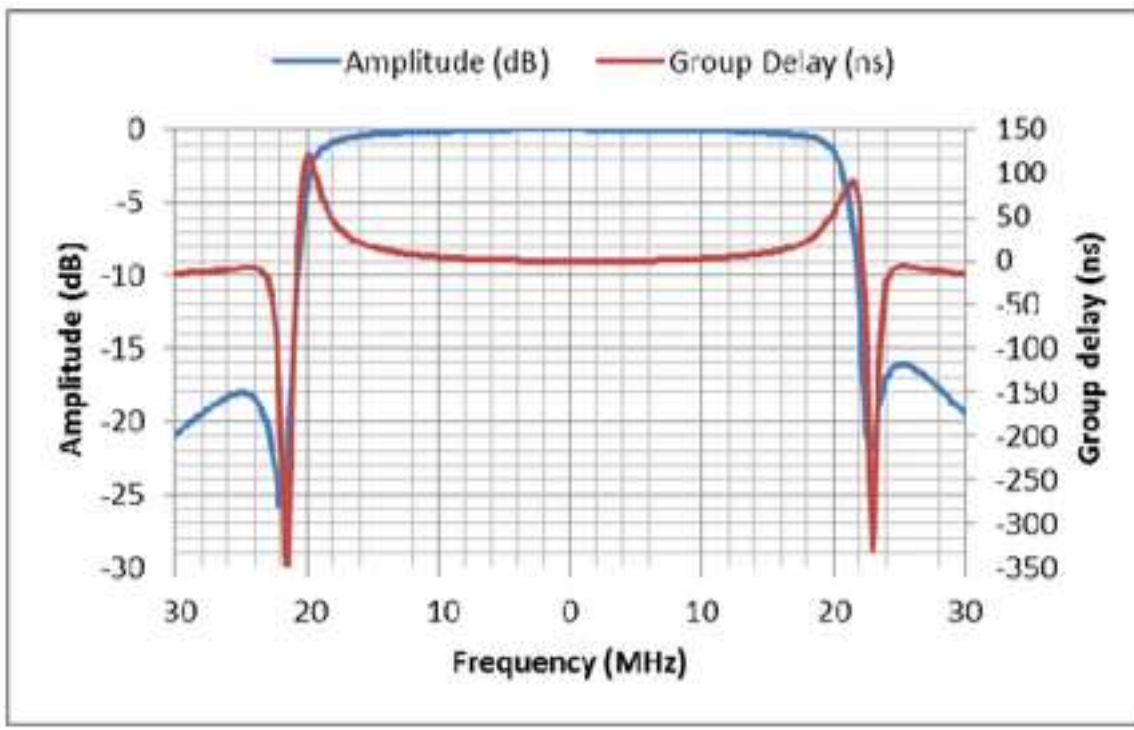
- **IMUX, Input multiplexer split wide band received signal into channels (33MHz,36MHz, 72MHz etc)**
- **Example 4 input is multiplexed into 16 channels**



Communication Satellites
Payload: IMUX

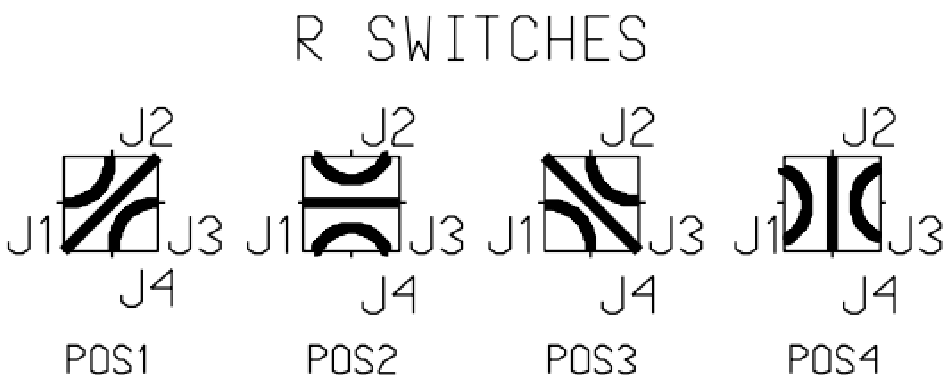
- **IMUX filter must reject signals outside of the band. Notice sharp decrease at ±20MHz. Amplitude response must be flat within the band.**
- **Example: 36 MHz channel**

- **Group delay is the derivative of filter phase transfer function with respect to frequency and it causes distortion of various frequency components with varying delays through filter, which in turn results in unwanted quadrature components causing crosstalk**



Communication Satellites
Redundancy

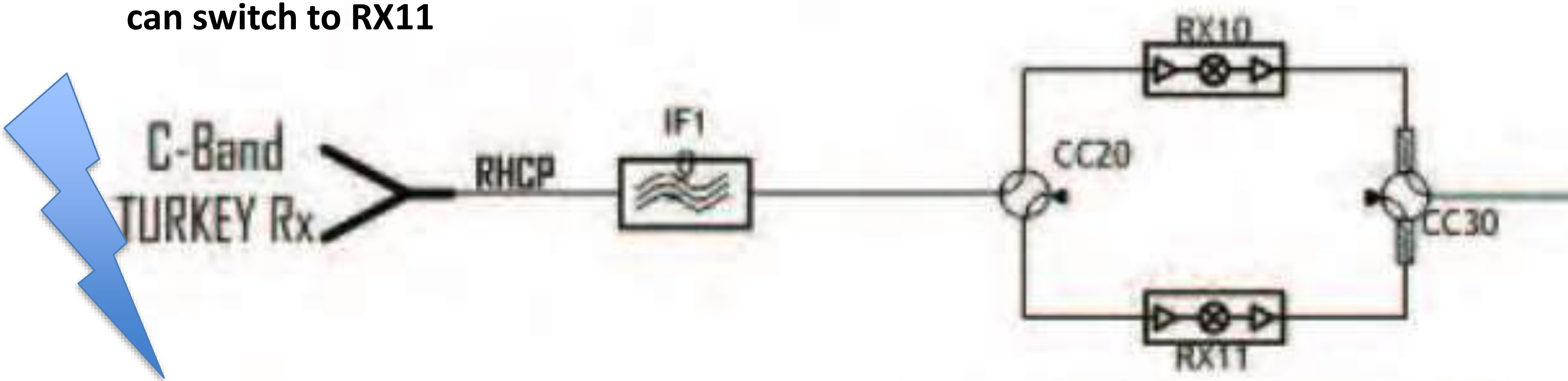
- **Satellite are in space and can not be repaired. Thus redundancy is required for reliable operation during 15 years.**
- **Redundancy is performed using 4 port R-switches.**

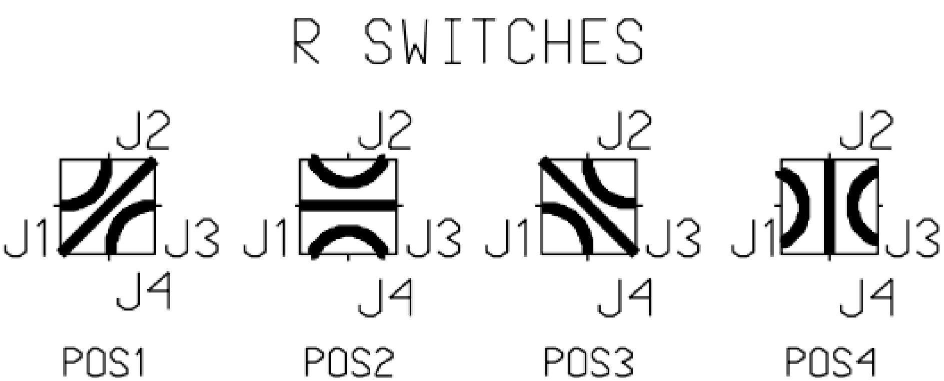


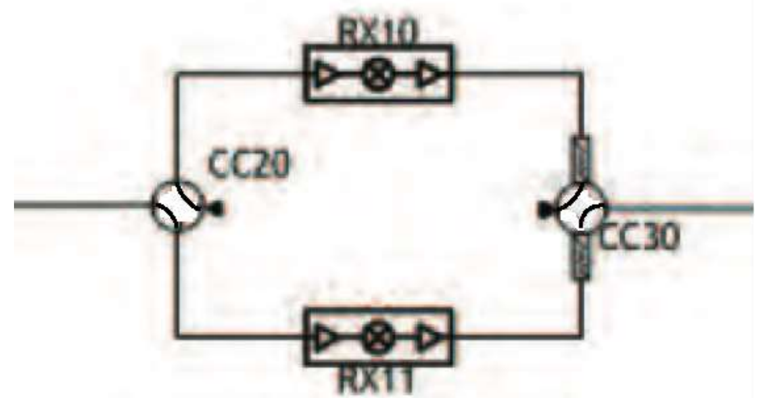
S. Gulgonul, E. Koklukaya, I. Erturk and A. Y. Tesneli, "Communication satellite payload redundancy reconfiguration," 2012 IEEE First AESS European Conference on Satellite Telecommunications (ESTEL), Rome, Italy, 2012, pp. 1-4, doi: 10.1109/ESTEL.2012.6400090.

Redundancy

- **Satellite are in space and can not be repaired. Thus redundancy is required for reliable operation during 15 years. Redundancy is performed using 4 port R-switches.**
- **Example: Two receivers, RX10 is active, RX11 redundant. If RX10 is in failure we can switch to RX11**

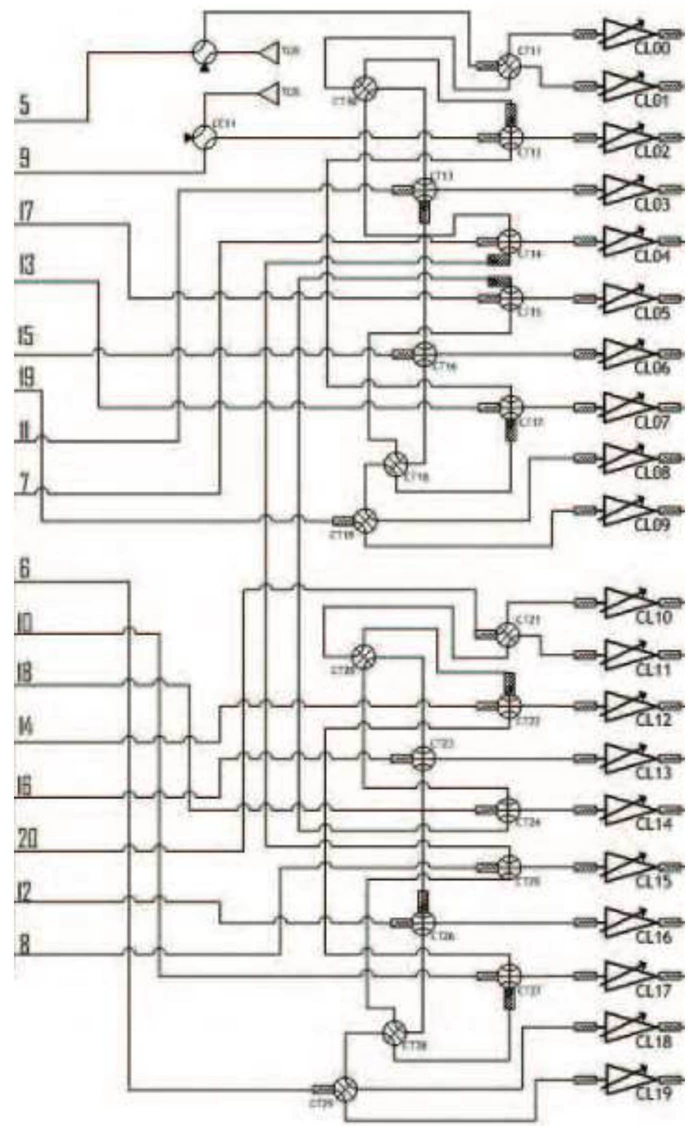






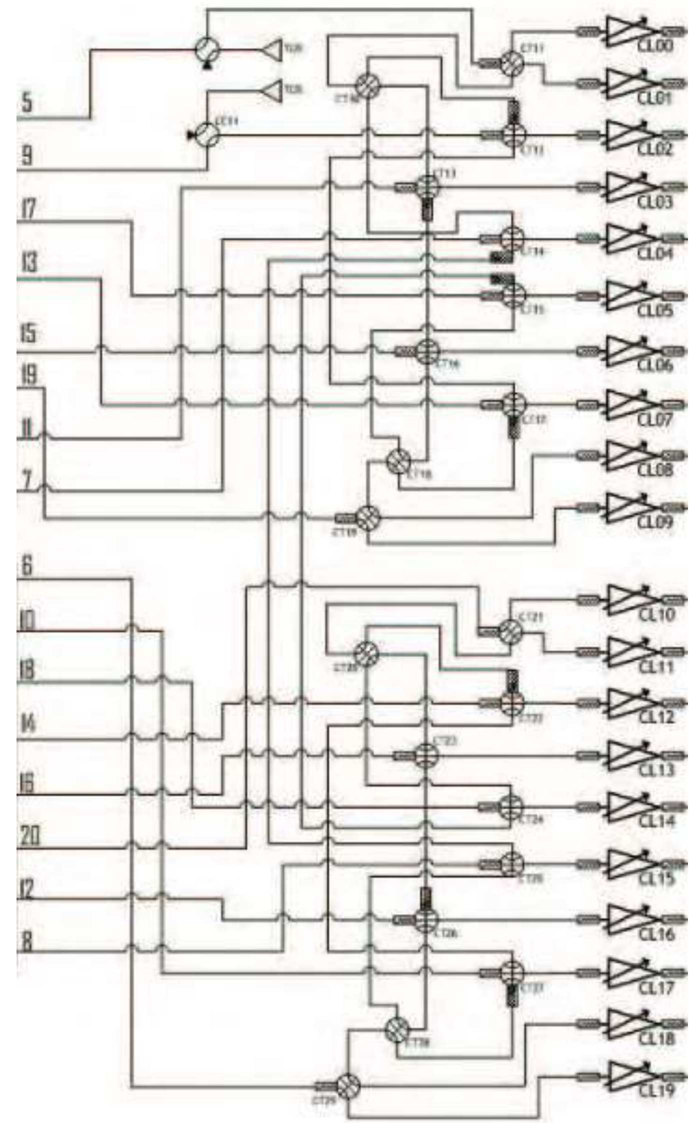
Communication Satellites
Redundancy

- **Redundancy becomes a complex problem with high number of channels**
- **Special software products are used to solve redundancy configuration problems**
- **Switches change their position using command from ground control station**
- **Example 16 channels use 20 TWTA's. 16 TWTA are active and 4 TWTA are redundant**



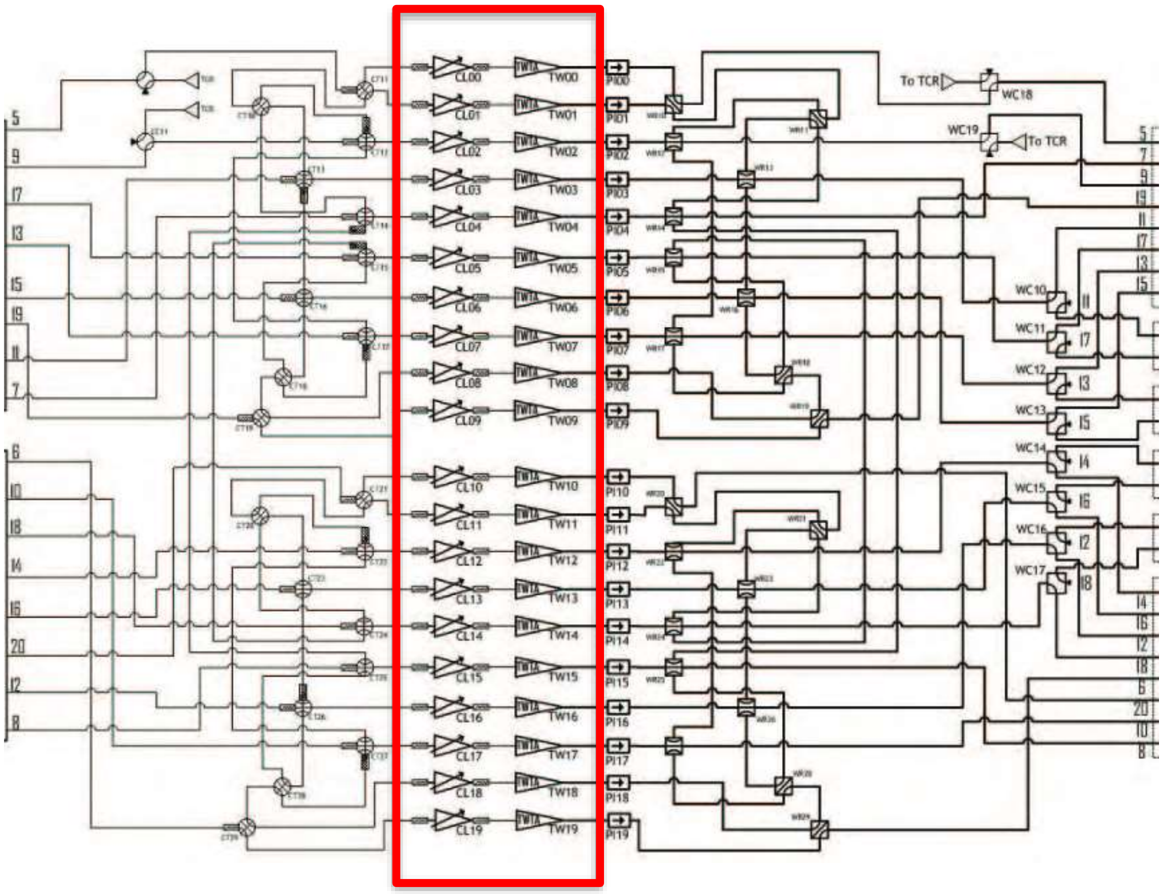
Communication Satellites
Redundancy Constraints

1. **Able to switch a redundant TWTA without causing an interruption on existing connections**
2. **Any n failure must be recoverable.**
3. **Don’t cross more than 3 switches**
4. **Use minimum number of switches (weight, cost)**



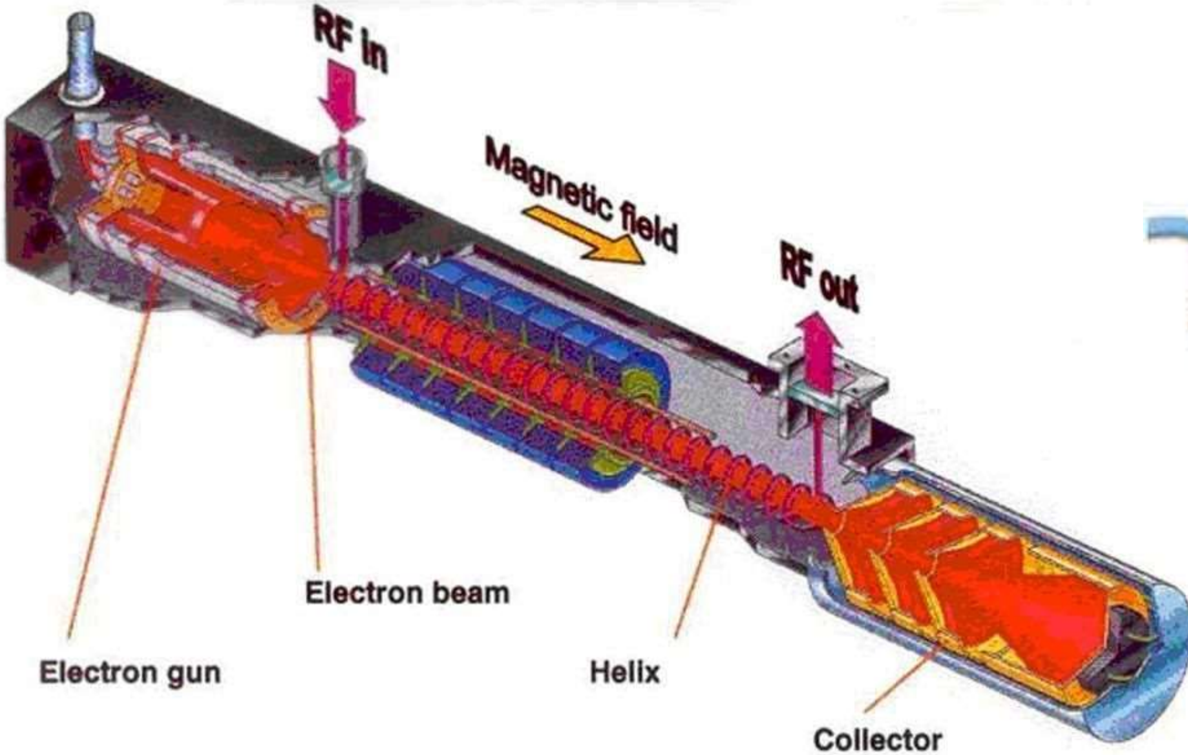
Communication Satellites
Payload: TWTA Section

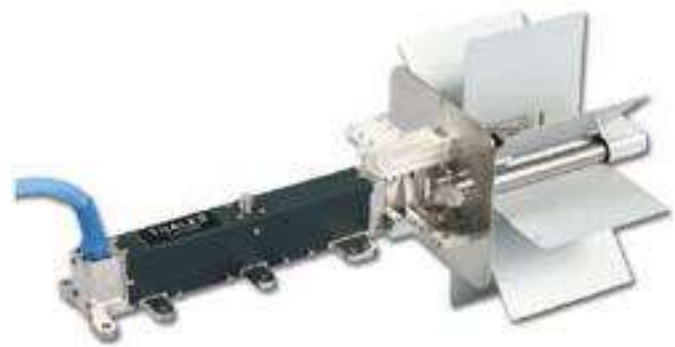
- **TWTA's are power amplifiers. There are redundancy switch matrix before and after TWTA's. Linearizer and Channel Amplifiers drives TWTA's. Isolators block reflection of amplified signals toward back**



Communication Satellites
Payload-TWTA

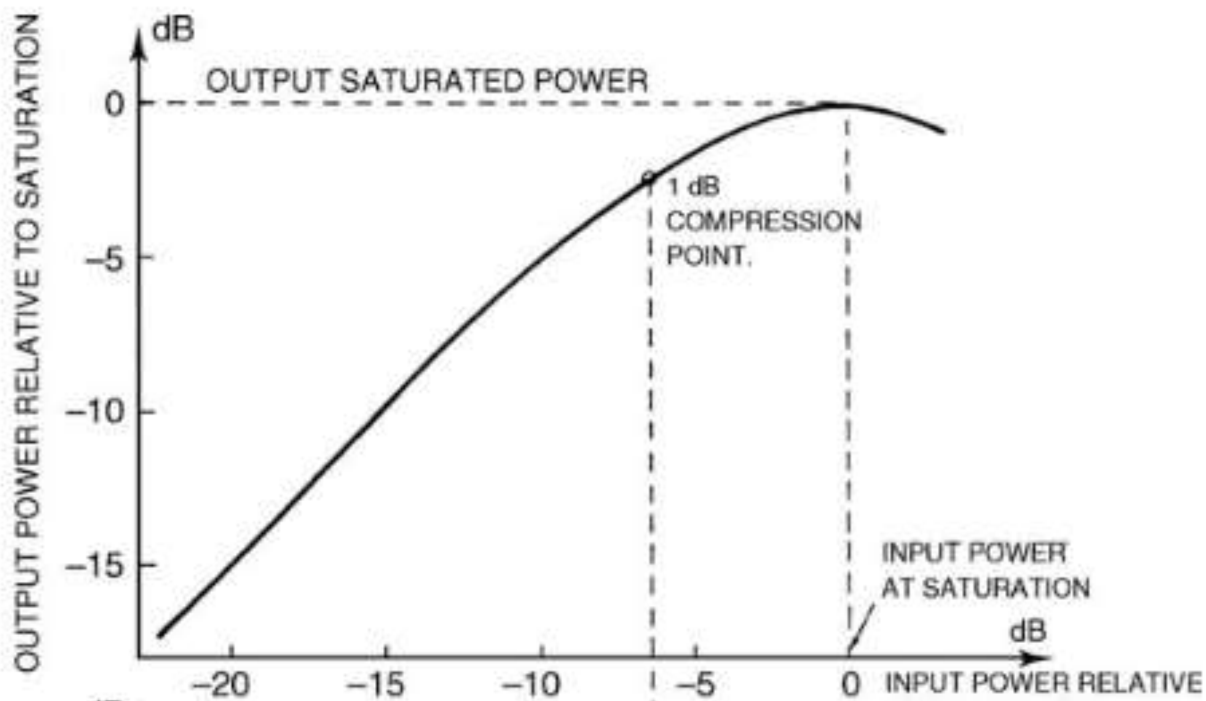
- **TWTA is a power amplifier. Uses electrons to magnify power of RF signal (like a transistor). SSPA's are replacing TWTA's slowly but TWTA's are still in use.**
- **Collector region is radiated cooled or conductive cooled**





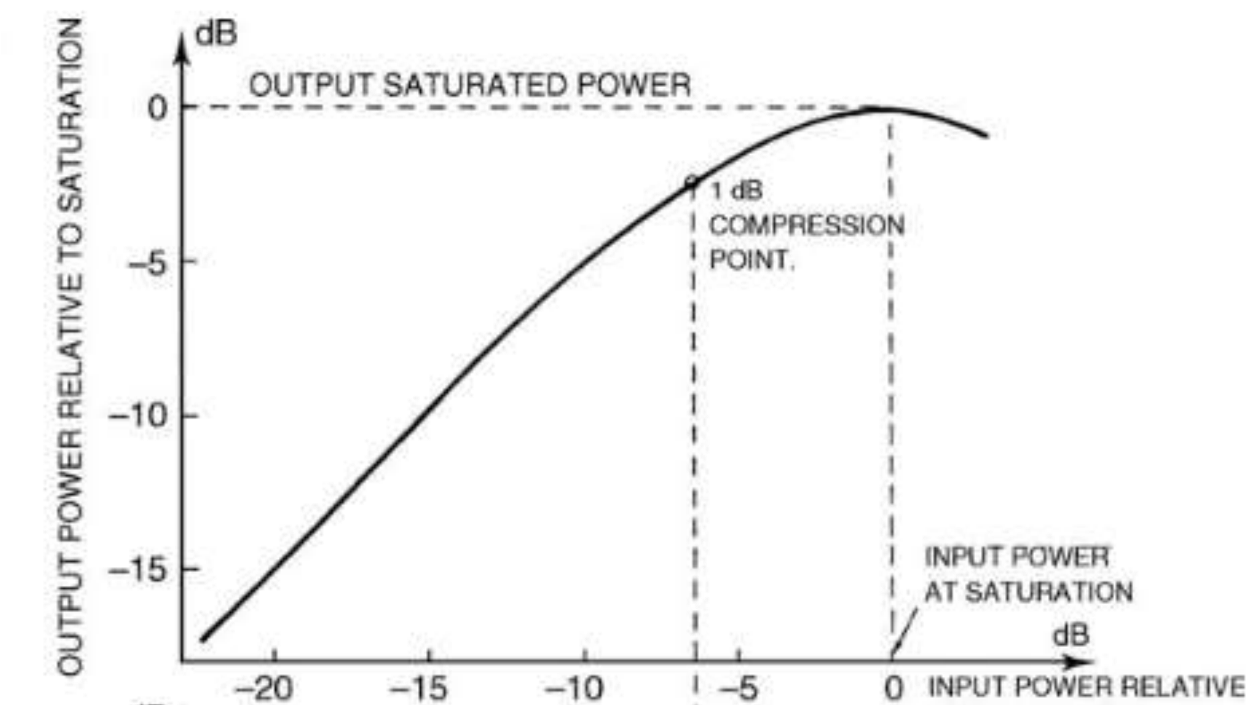
Communication Satellites
Payload-TWTA

- **TWTA is not a linear device. AM/AM curve shows input power normalized to input back-off (IBO) to output power normalized to output back-off (OBO). Near to saturation output power is maximum but nonlinearity is high.**
- **AM/AM (Amplitude Modulation) curve relates the input signal power normalized as input back-off (IBO) to output signal power normalized as output back-off (OBO). The slope of this curve is called AM/AM conversion coefficient and expressed in dB per dB .**



Communication Satellites
Payload-TWTA

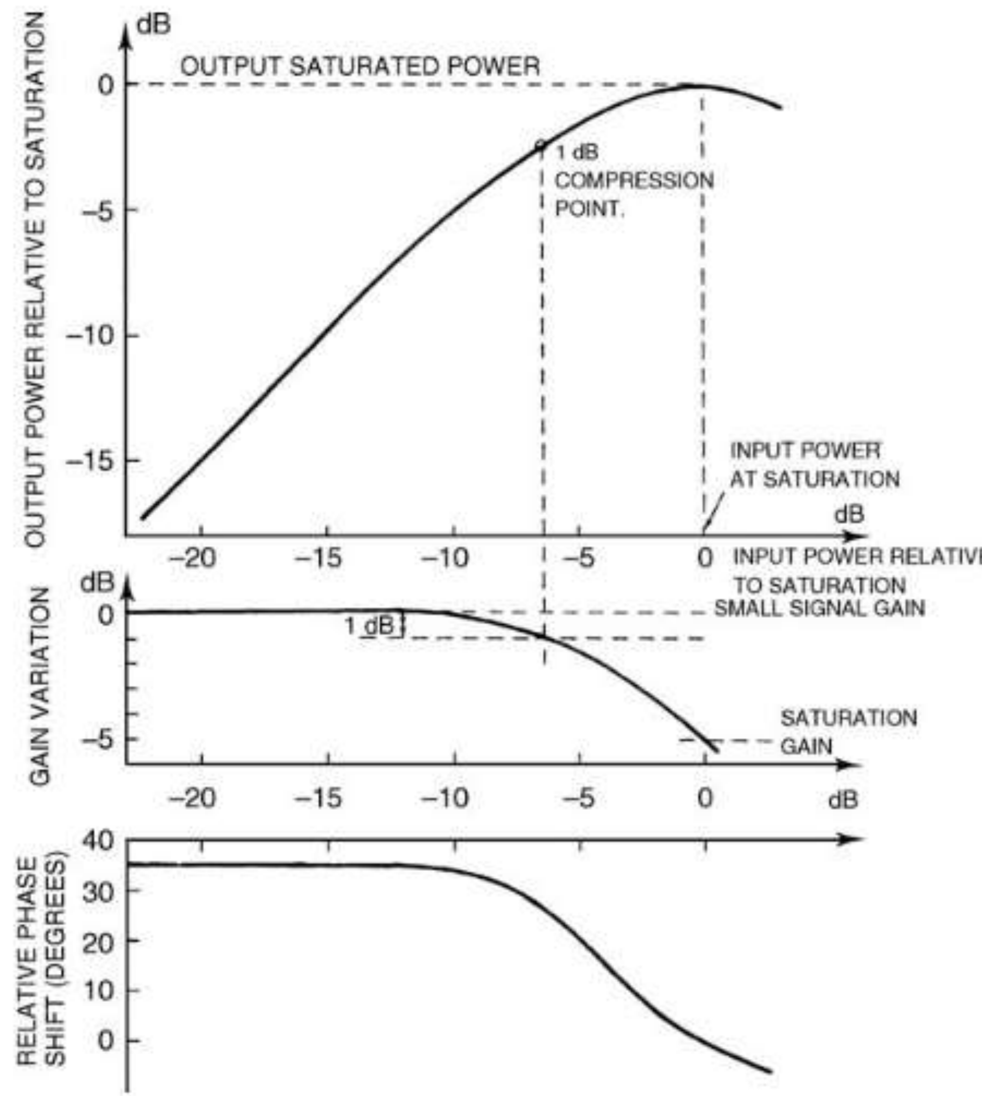
- **The entire hurdle is about finding the optimum operating point of the HPA over this curve which is closest to the saturation point in order not to waste very critical EIRP while not sacrificing the link performance to nonlinear degradations.**



Communication Satellites
Payload-TWTA

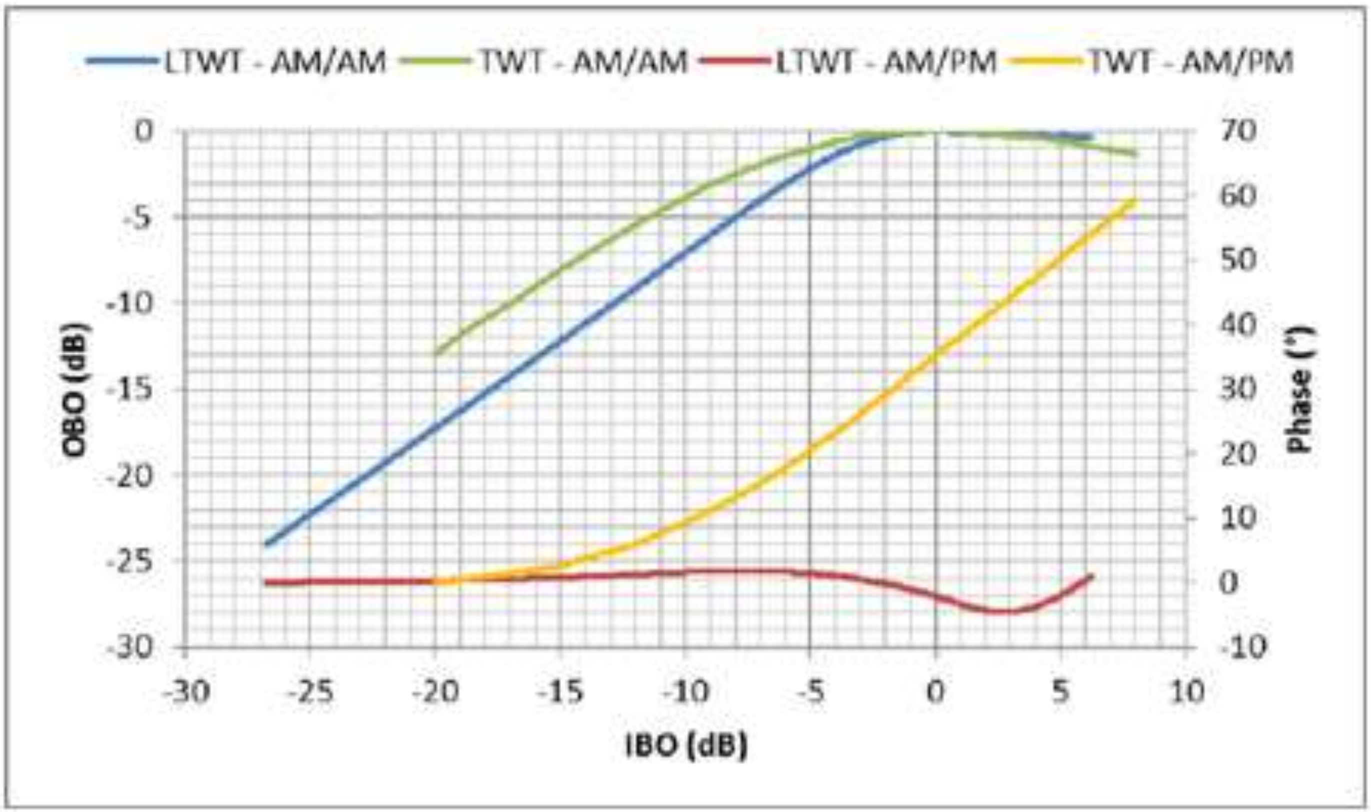
- **AM/PM curve shows input power to phase shift. This is also another cause of non linearity of TWTA. Slope of the curve is named as AM/PM conversion factor or coefficient degree/dB**

- **Nonlinear behavior is the introduction of phase shifts between the input and the output by HPA. Such non-constant phase shift is especially harmful for digital PSK modulations used in satellite communications since the information is carried by the phase of the signal**



Payload-TWTA

- **Linearized TWTA's has better performance, brings linear region close to saturation and limits the phase shift.**
- **AM/AM and AM/PM curves can be presented on the same graph**



TWTA Single Carrier

- **Single carrier will have products at multiple of input frequency which can not be at the same transponder.**
- **Transponders have output filters to remove such products.**
- **Nonlinear output can be modeled as a polynomial of input signal**

$$V_o = k_0 + k_1 V_i + k_2 V_i^2 + k_3 V_i^3 + \ldots$$

$$V_i = A\cos(wt)$$

$$\cos^2(wt) = \frac{1}{2} + \frac{1}{2}\cos(2wt), \cos^3(wt) = \frac{3}{4}\cos(wt) + \frac{3}{4}\cos(3wt)$$

$$V_o = \ldots + (k_1 + \frac{3k_3}{4})A\cos(wt) + (\ldots)A\cos(2wt) + \ldots$$

TWTA Multicarrier Intermodulation

- **Multiple carrier may have products close to the fundamental frequencies. 2w1-w2 and 2w2-w1 may be in the same transponder.**
- **Example, f1=11480MHz, f2=11500MHz, 2f1-f2=11460, 2f2-f1=11520 may exist in the same 72MHz transponder with center frequency of 11492MHz.**
- **Thus multicarrier transponders are operated with sufficient back-off in linear region**

$$V_o = k_0 + k_1 V_i + k_2 V_i^2 + k_3 V_i^3$$

$$V_i = A_1 \cos(w_1 t) + A_2 \cos(w_2 t)$$

$$V_o = DC + \ldots + (\frac{3}{4} k_3 A_1^2 A_2 + ..) \cos((w_1 \pm 2 w_2) t) + ..$$

$$+(\frac{3}{4} k_3 A_1 A_2^2 + ..) \cos((w_2 \pm 2 w_1) t) + \ldots$$

TWTA Multicarrier Intermodulation

9.2.1.3 *Power transfer characteristic in multicarrier operation*

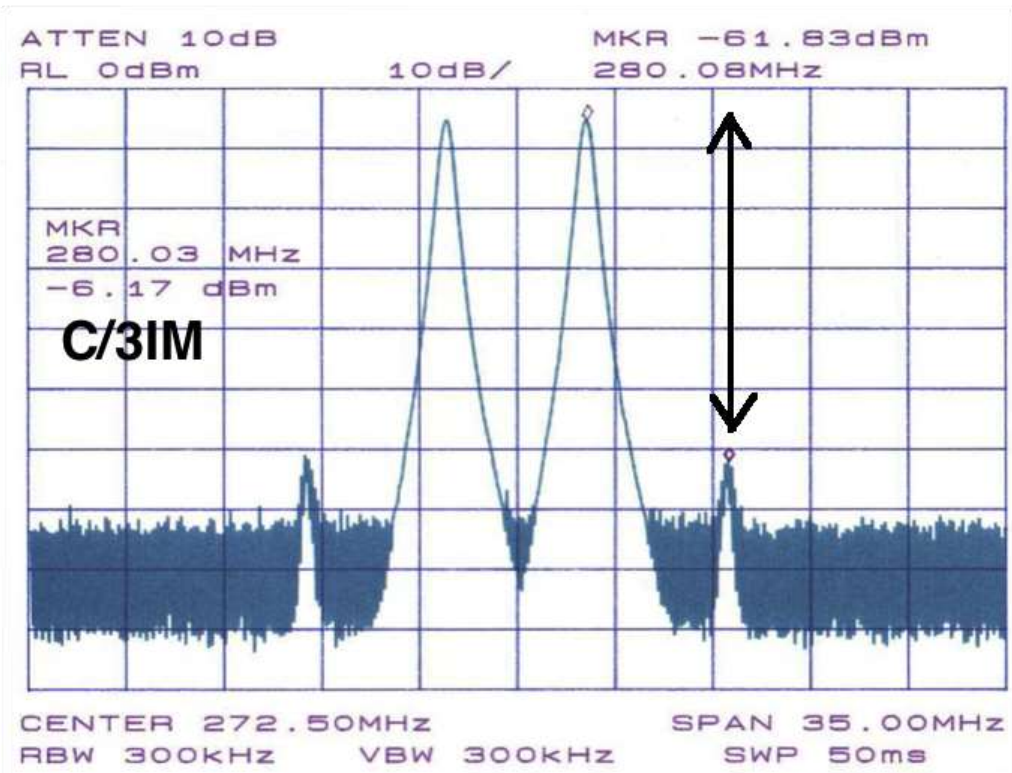
The signal applied at the input of the device is now considered as the sum of sinusoidal unmodulated carriers. It is, therefore, put in the form:

$$S_{\mathrm{i}} = A \sin \omega_1 t + B \sin \omega_2 t + C \sin \omega_3 t + \cdots \quad \text{(V)}$$

Expansion of the instantaneous amplitude of the output signal S_{o} using equation (9.2) results in the appearance of components at the input angular frequencies (ω_1, ω_2, etc.) and at frequencies corresponding to linear combinations of these frequencies (*intermodulation products*). These intermodulation products have been defined in Section 6.5.4. Only odd intermodulation products occur in the vicinity of the input frequencies. On the other hand, the amplitude of these intermodulation products decreases with their order. The most troublesome are third-order intermodulation products at frequencies $2f_{\mathrm{i}}-f_{\mathrm{j}}$ and $f_{\mathrm{i}}+f_{\mathrm{j}}-f_{\mathrm{k}}$.

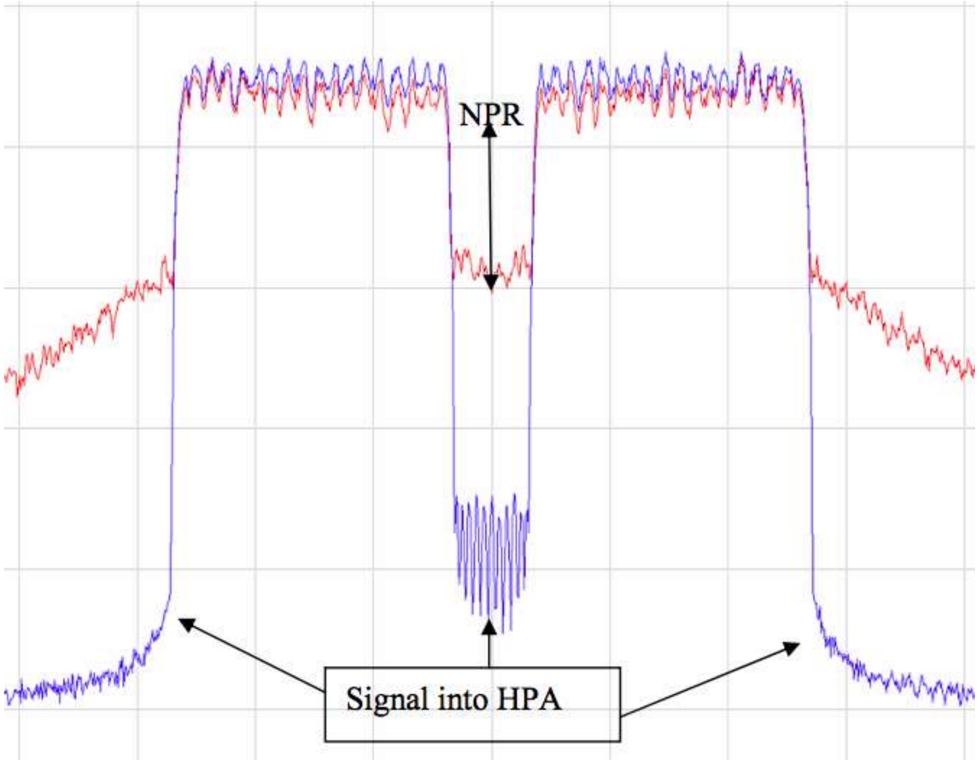
Communication Satellites
Carrier to 3IM

- Carrier to 3rd order intermodulation (C/3IM) can be measured using spectrum analyzer. **2f1-f2 and 2f2-f1**
- Noise level must be below intermodulation.
- C/3IM is given TWTA datasheets for OBO



Communication Satellites
TWTA Noise Power Ratio

- NPR Noise Power Ratio is another method to measure linearity of the transponder. A white noise with a notch filter at the center of the transponder is used to measure NPR



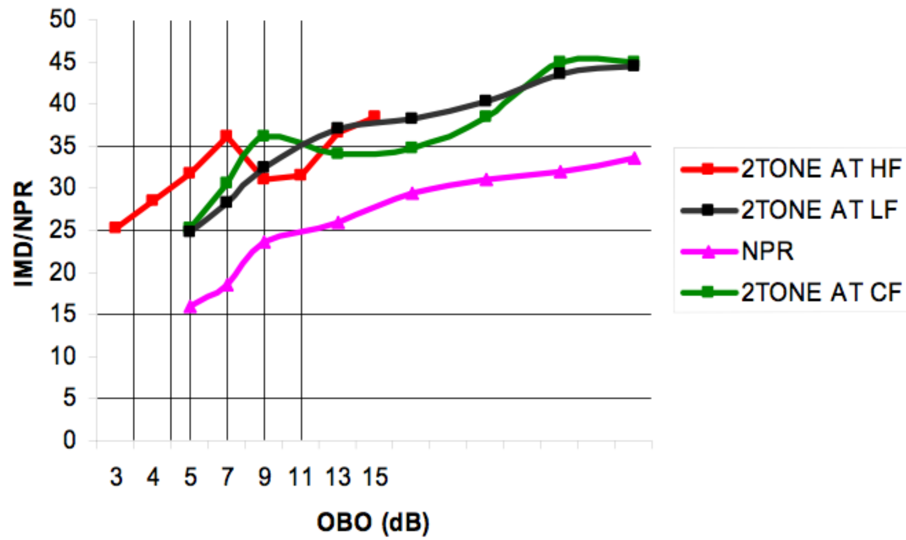
$$NPR = 10\log\left(\frac{N_0}{N_{0IM}}\right)$$

N_0 : *Noise outside notch*

N_{0IM} : *Noise inside notch*

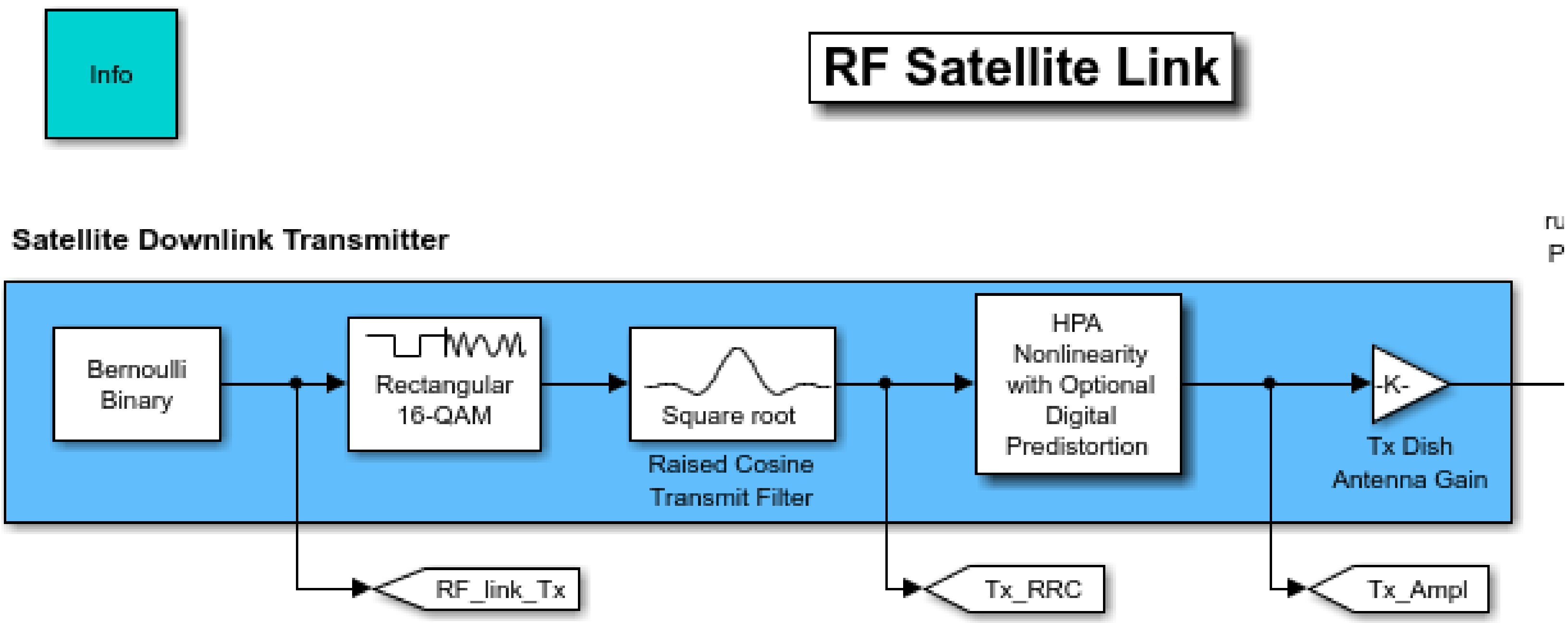
Communication Satellites
IM vs NPR

- NPR is more pessimistic compare to two carrier intermodulation measurements.
- Typical 3rd order IM is -25dBc at 4dB OBO while NPR is -19 dBc for ground TWTA's while IM is -19dBc for space TWTA's NPR is -17dBc
- C/3IM or NPR show linearity of the TWTA and can be used in detailed link budgets



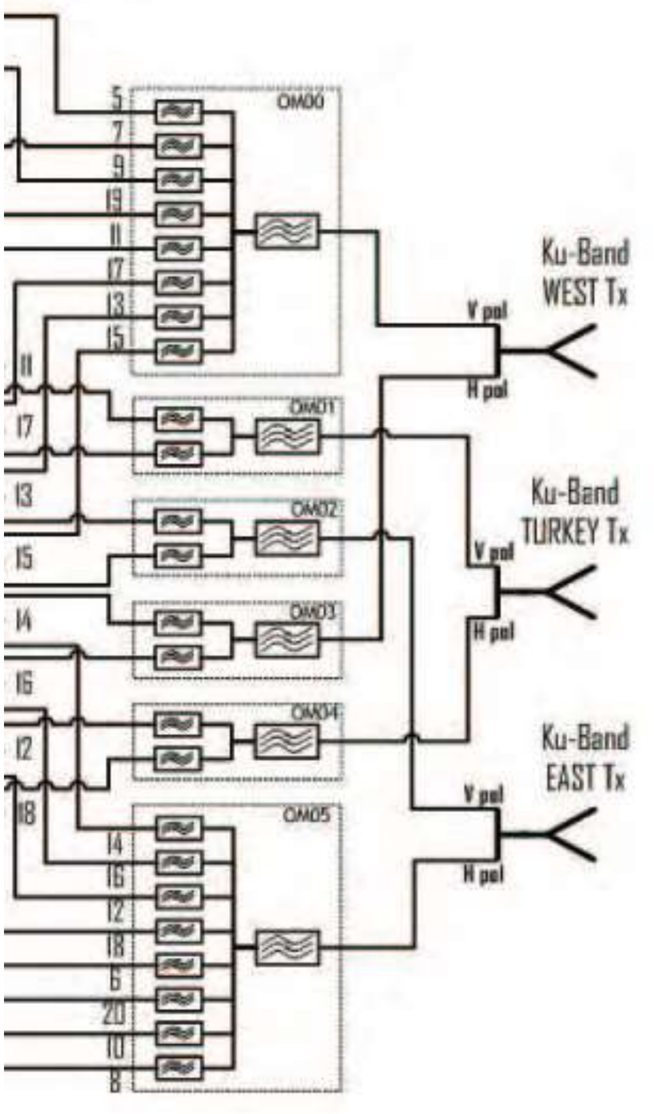
Communication Satellites
TWTA Modeling

- There are different approaches for TWTA nonlinearity modeling (Saleh, Rapp etc).
- There is an example in MATLAB for QAM.
- Term Project idea: develop a Simulink model with TWTA nonlinearity using QPSK



Communication Satellites
Payload: OMUX Section

- **OMUX, output multiplexers combine power amplified signals and feed related antennas.**
- **Example : 3 coverage with two polarization requires 6 OMUX**



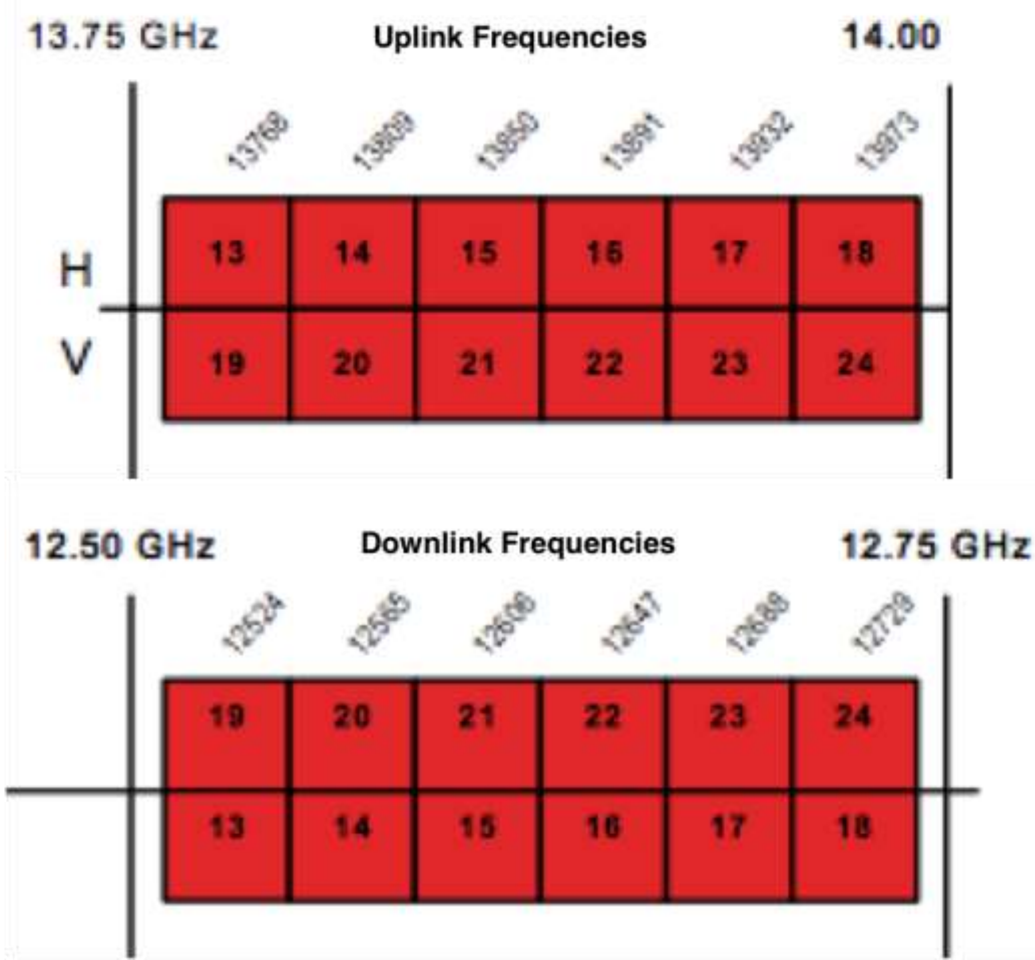
Communication Satellites Frequency Bands

- **Range of frequencies are named in satellite communication.**
- **These names mostly comes from ITU (International Telecommunication Union) regulations or sometimes from industrial use**
- **Ku, BSS (Broadcast Satellite Services), FSS (Fixed Satellite Services) is used mainly for TV Broadcasting and data communication**
- **Ka band is new and used in data communication with spot beams**
- **X band is used by military communication**
- **C band is the oldest band used for TV and data**

Band	Downlink(MHz)	Uplink(MHz)
C	3400-4200	5850-6700
X	7900-8400	7250-7750
Planned FSS	10700-10950 11200-11450	12750-13250
Standart Ku	10950-11200 11450-11700	14000-14500
BSS	11700-12500	17300-18100
Extended Ku/FSS	12500-12750	13750-14000
Ka	17700-21200	27500-31000
Ka BSS	21400-22000	24650-25250

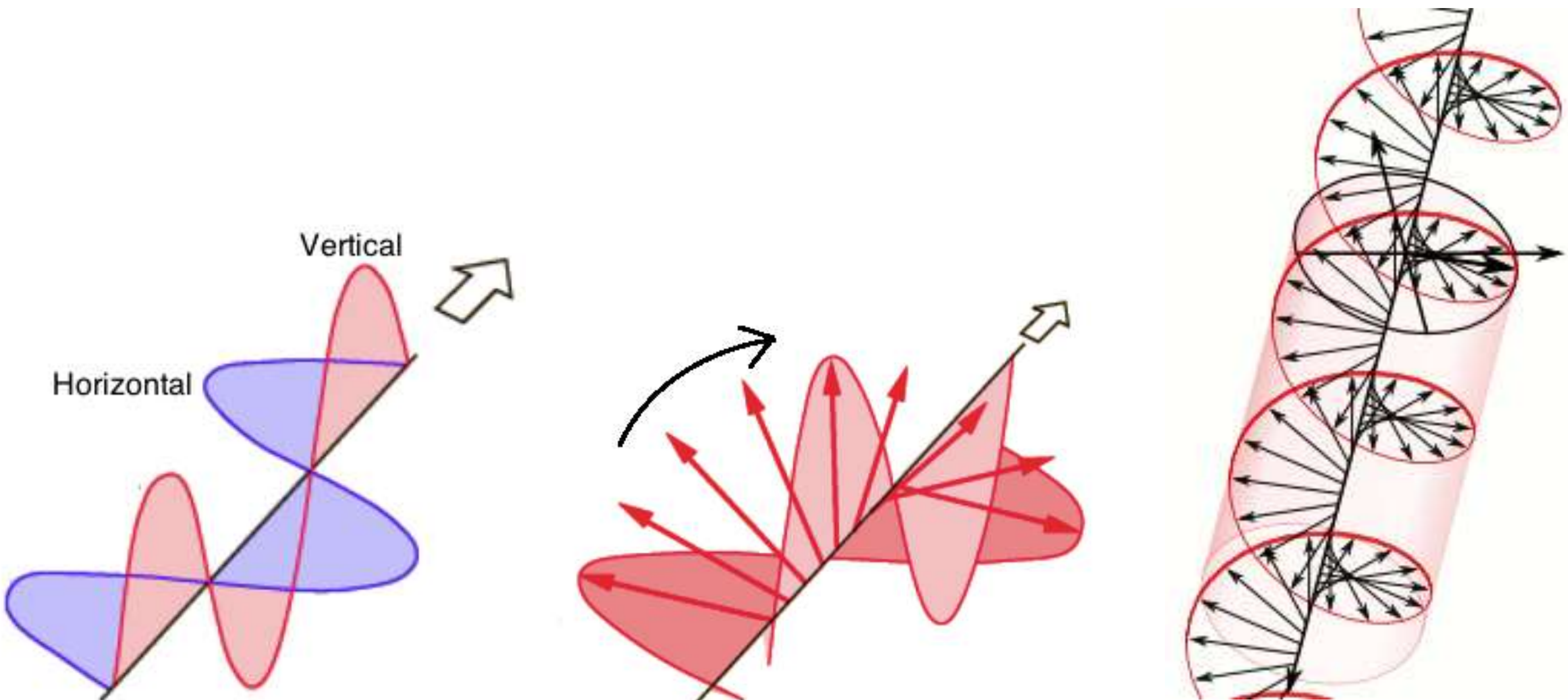
Communication Satellites
Frequency Plan

- Frequency plan of a satellite shows transponders uplink and downlink frequencies.
- Example: uplink 13.750-14.000 GHz range with 12 transponders. Horizontal and vertical polarizations.
- Downlink frequency range is 12.500-12-750GHz
- DOCON LO frequency:13768-12524=1244 MHz
- Uplink and downlink at different polarization
- Transponder center frequencies are given (transponder bandwidth 36MHz)
- Single Coverage



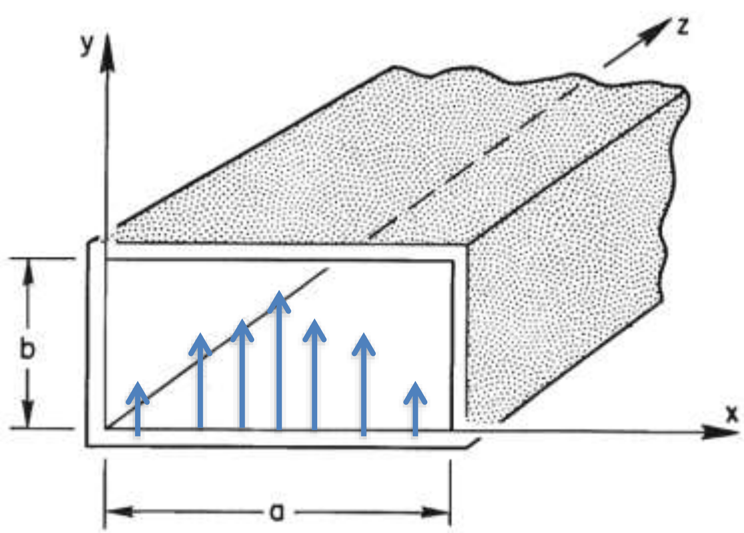
Communication Satellites
Polarization

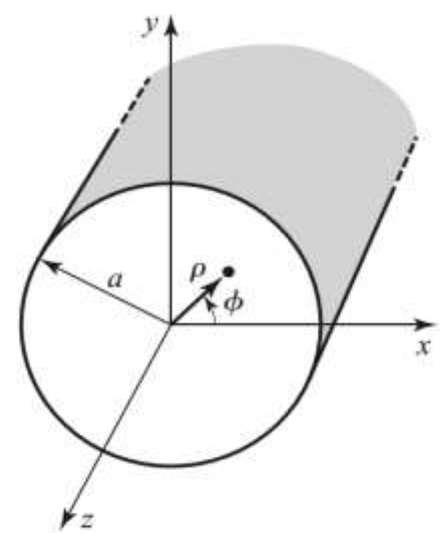
- **Linear polarization (Horizontal-Vertical) is widely used in Ku band.**
- **Circular polarization (RHCP-LHCP) is used in C band, Ka band.**
- **Frequency is a limited source in satellite communication. Polarization discrimination allows double use of the same frequency.**



Communication Satellites
Polarization

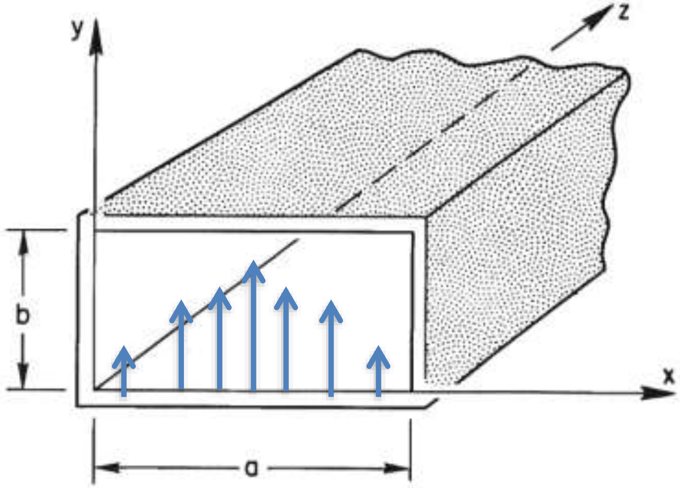
- **Polarization is defined by the waveguide behind the feed horn. Rectangular waveguides can carry linear polarization and circular waveguides can carry circular waveguides. Dimensions of waveguide are related to the frequency range.**
- **Example: Vertical polarization E-Fields**

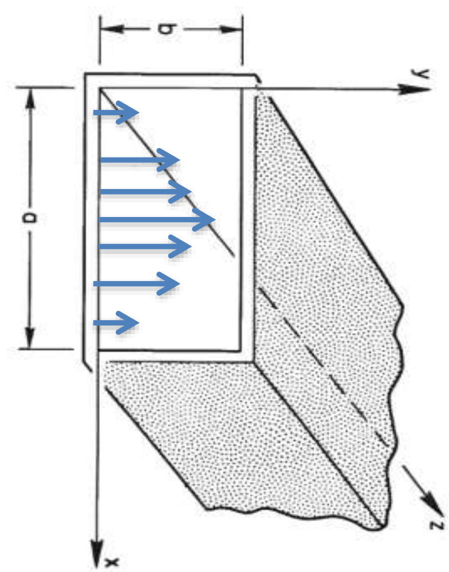




Communication Satellites
Cross Polarization

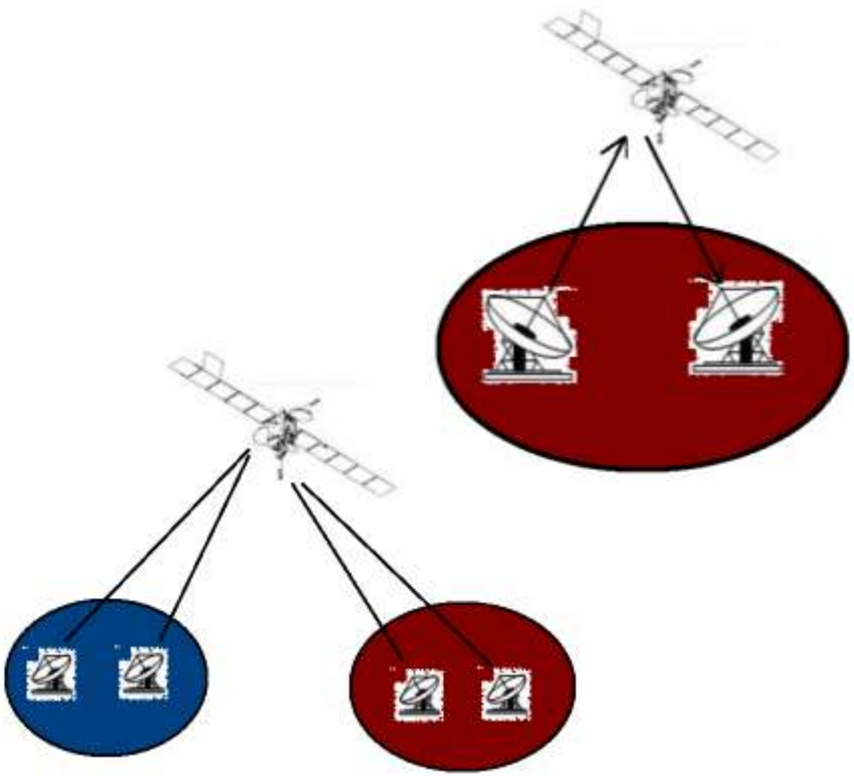
- **Polarization of satellite transmit and ground receive antennas must be same.**
- **If not there x-polarization interference at the same frequency.**
- **Polarization isolation is suppression dB of antenna for the reverse polarization. This is typically 25-35dB for Ku band linear polarization.**
- **Polarization isolation of the antenna is coming from manufacturing. But also operationally polarization adjustment of the feed has to be done correctly**
- **circular polarization suppression 20-30dB**

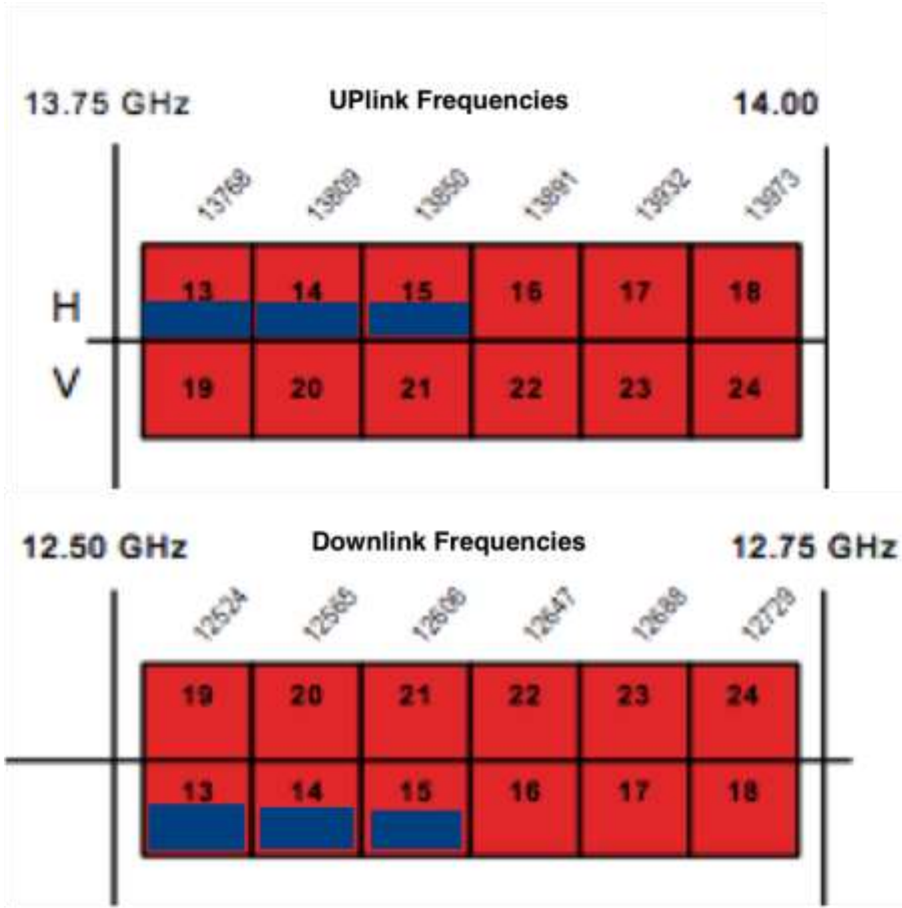




Communication Satellites
Frequency Plan

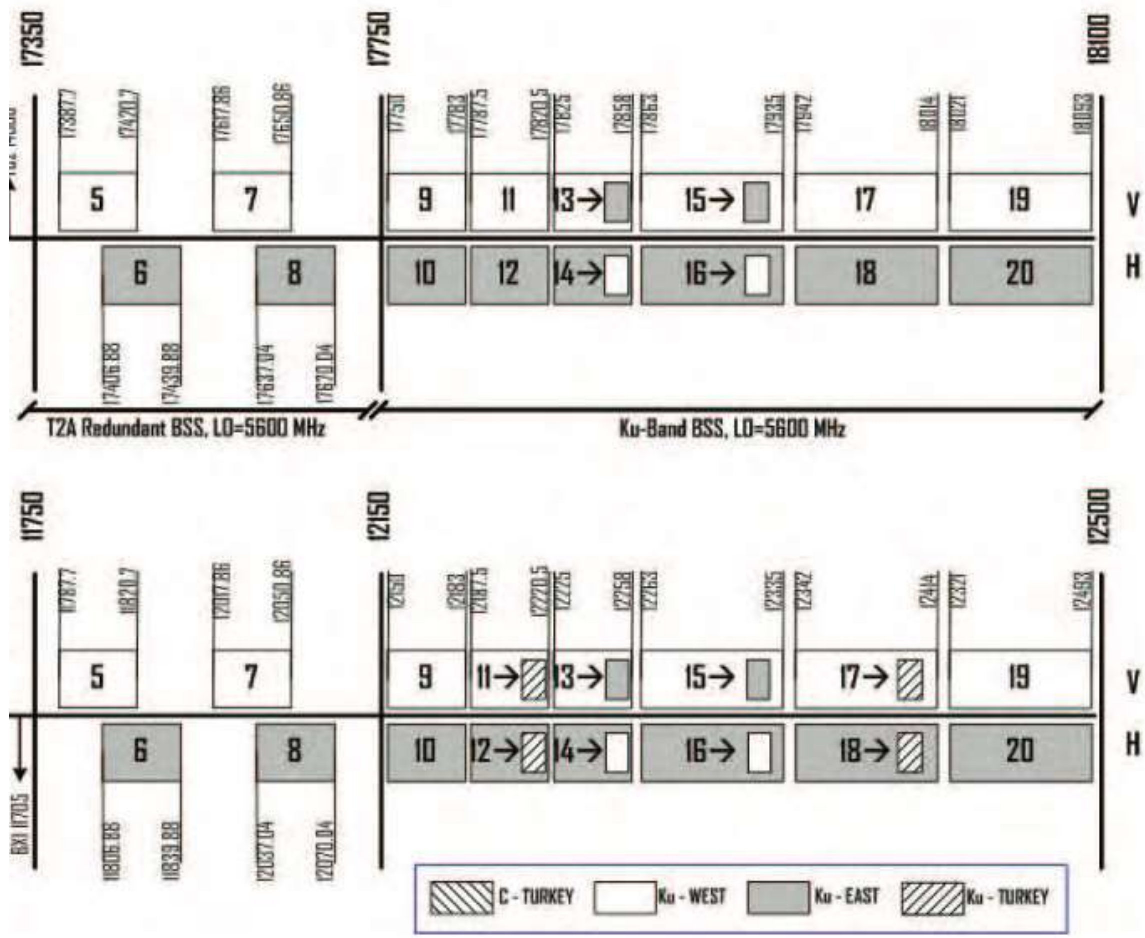
- **Transponders can be used for single coverage area or switchable to use at different coverage areas. Example transponders 13,14,15 can be used at both coverage areas.**





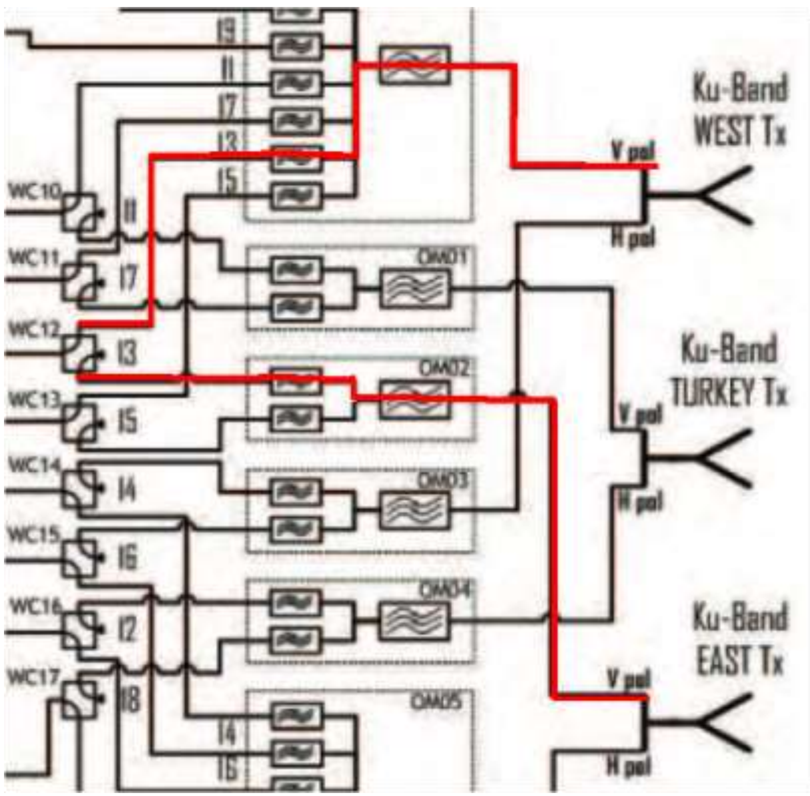
Communication Satellites
Frequency Plan

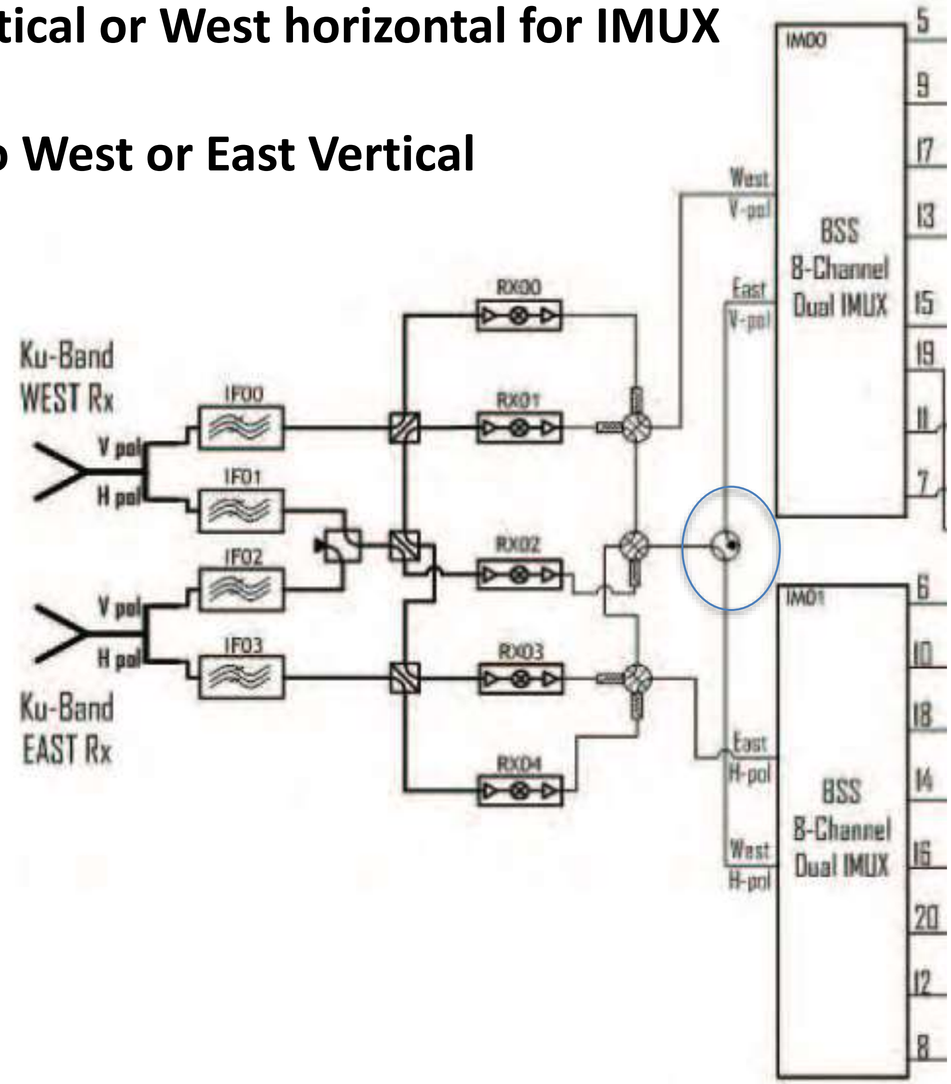
- **Example: Tusat BSS frequency Plan.**
- **3 coverage areas: East, West, Turkey**
- **Some of the channels are switchable such as 13,15,15,16**
- **How we can design this switchability ?**



Communication Satellites
Frequency Plan

- **The switch shown can select East vertical or West horizontal for IMUX input.**
- **Output section: ch13 can be routed to West or East Vertical**





Communication Satellites Frequency Plan

- **TV frequencies, coverage, modulation, symbol rate, FEC etc parameters can be found in operators web page or www.lyngsat.com**
- **Turksat Orbital Locations are 31, 42 and 50 degree east**

TÜRKSAT

TÜRKSAT UYDU FREKANS LİSTESİ

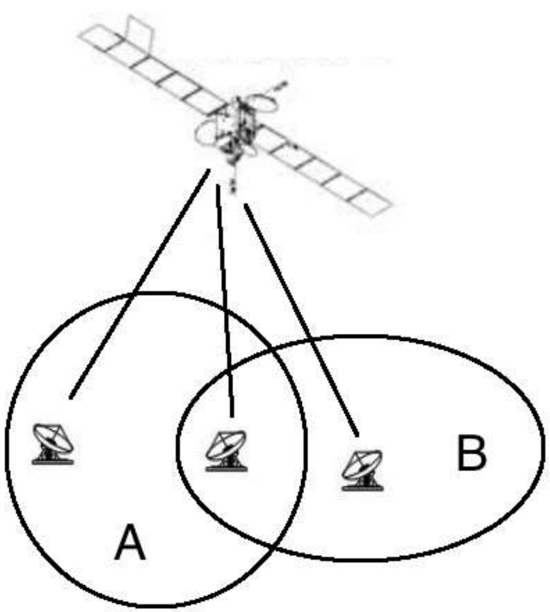
Arama | Paket: Tümü | Uydu: Tümü | Kapsama: Tümü | Polarizasyon: Tümü | Yayın: TV Kar | Şifreleme: Tümü | PDF | CSV

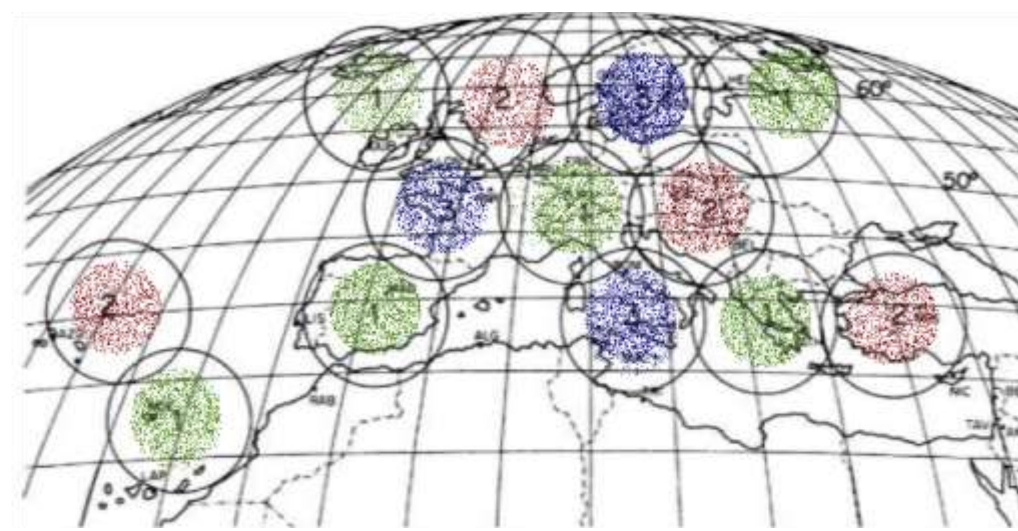
Kanal	Frekans	Polarizasyon	Kapsama	SR	FEC	V-PID	A-PID	Uydu
1 AN TV (TV)	11096	V - Dikey	Batı	30000	5/6	2311	2411	Türksat 3A

Frequency Beam EIRP (dBW)		*Provider Name* Channel Name		System Encryption	SR-FEC SID-VPID		ONID-TID C/N lock APID Lang.
11054 V tp 10 West 52	TRT	***TRT***		DVB-S2	30000-3/4 8PSK		1070-31001 7.9
		TRT Çocuk	F S	MPEG-4/HD	10600	1600	1700 Tu
		TRT 1	F S	MPEG-4/HD	10601	1601	1701 Tu
		TRT Haber	F S	MPEG-4/HD	10602	1602	1702 Tu
		TRT Spor	F S	MPEG-4/HD	10603	1603	1703 Tu

Communication Satellites
Frequency Reuse

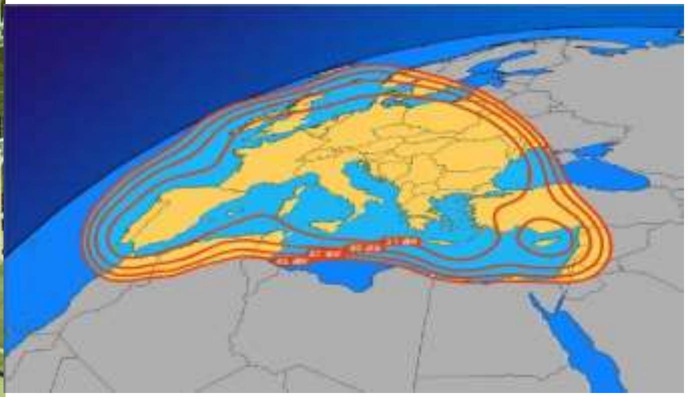
- **The same frequencies can be used if coverage areas are isolated from each other and not overlapping. Spot beams allow reuse of the same frequencies 3 or more times and increase the capacity of the satellite.**
- **If the same frequency used in overlapping coverage areas, users at intersection will receive two different signals at the same frequency and can not work.**

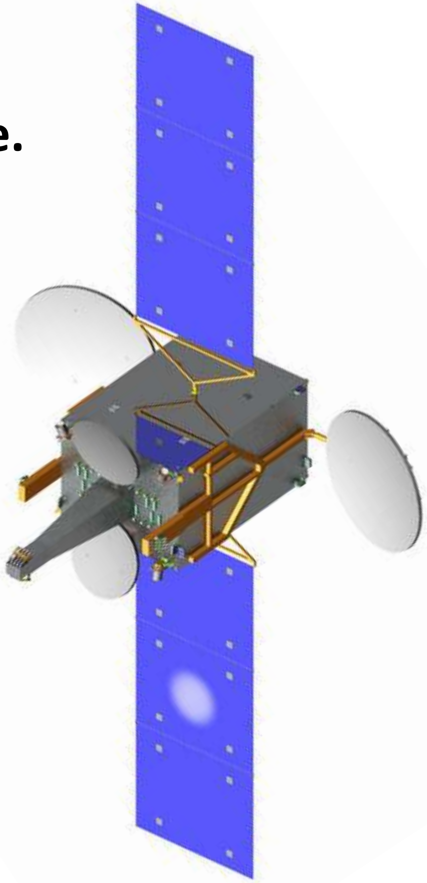




Communication Satellites Payload-Antenna

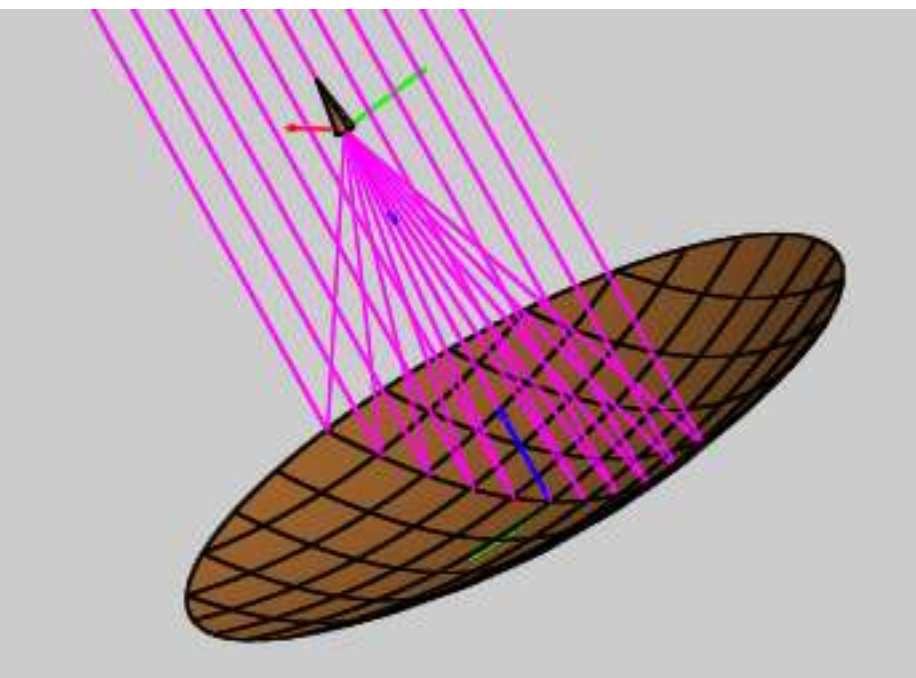
- **Deployable single reflector antennas are used in west and East Panel with diameters up to 2.3 meter. Smaller (0.6m to 1.3m) dual reflector antennas (Cassegrain) are preferable at Earth Deck Panel. They may be steerable but not deployable.**
- **Reflectors are shaped to meet coverage polygons.**

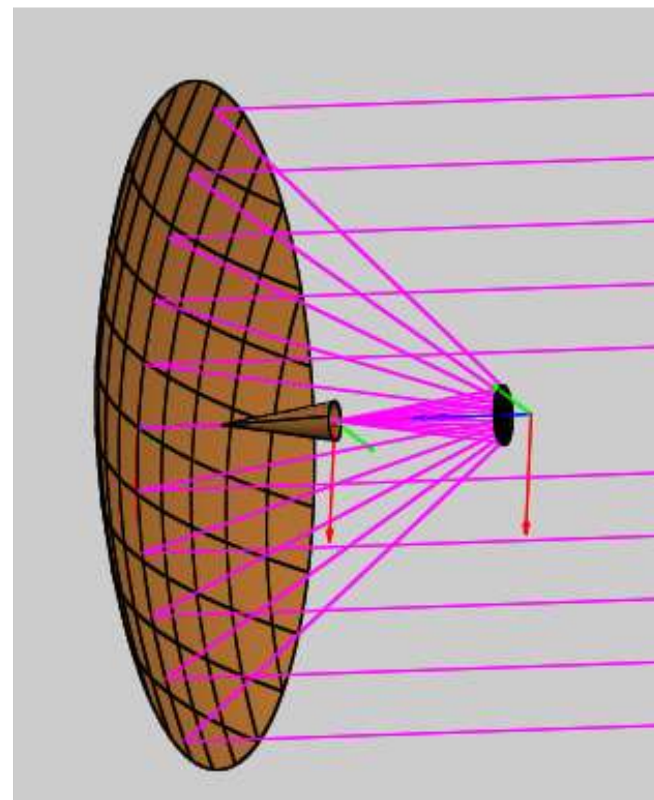




Communication Satellites
Single Reflector-Dual Reflector

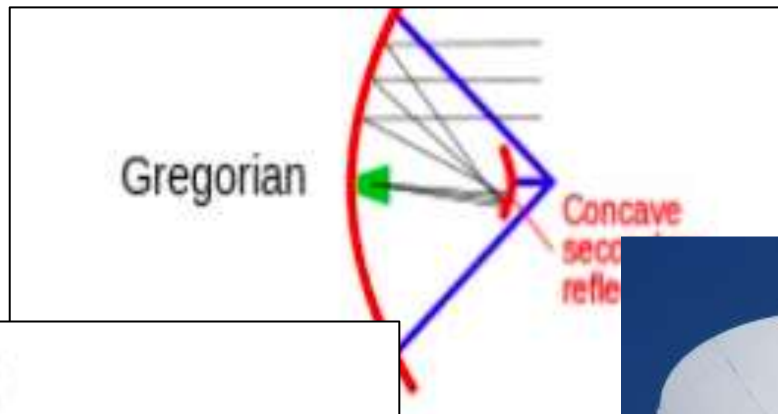
- **Single reflector: electromagnetic waves transmitted from the feed reflected to antenna looking angle.**
- **Dual reflector: reduces the focal length, suitable to use in Earth Deck Panel**

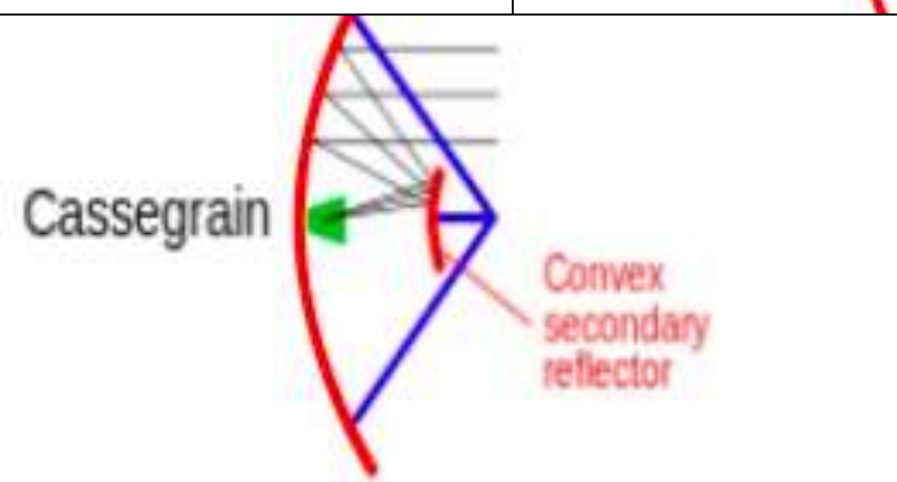




Communication Satellites
Dual Reflector

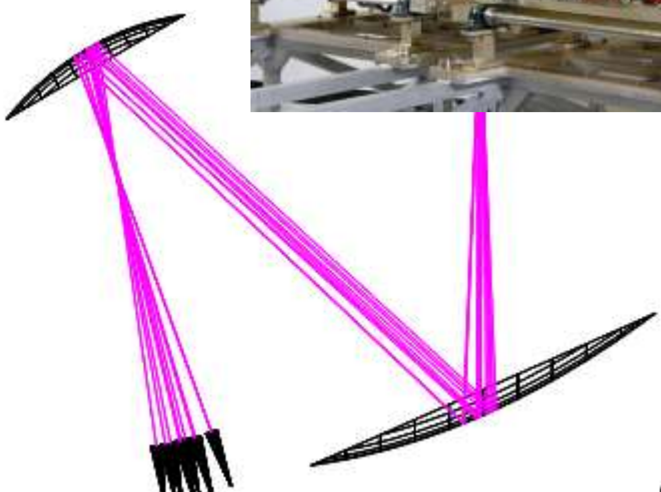
- **Dual reflector: shape of sub-reflector can be convex (Cassegrain) or concave (Gregorian).**
- **Dual reflector is preferred at higher diameters at Earth Stations (Mechanical advantage: heavy feed assembly mounted on main structure).**

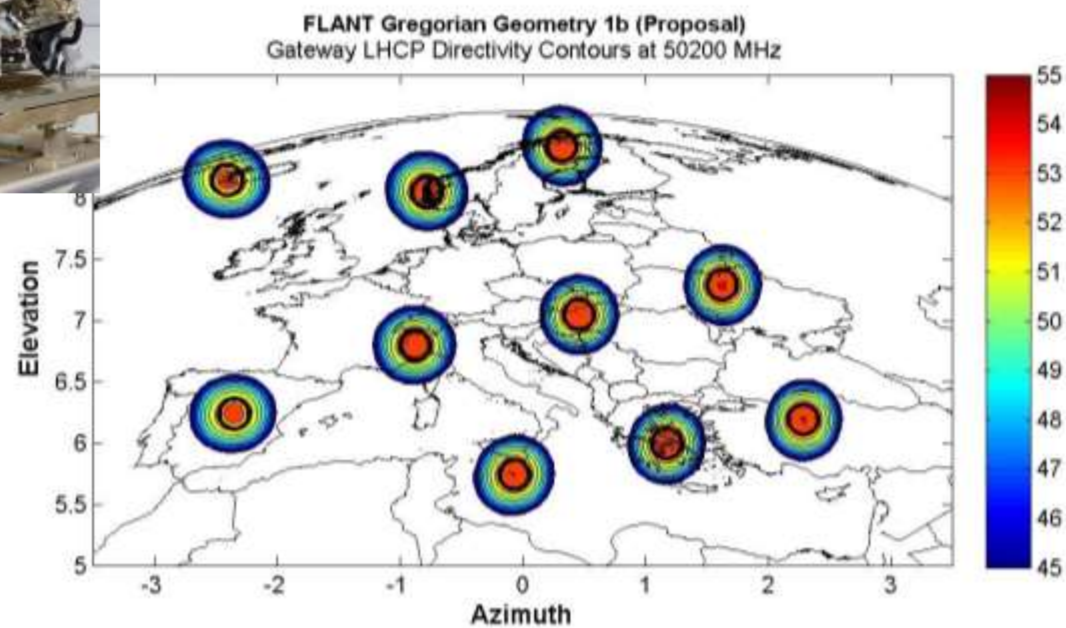




Communication Satellites
Payload-Antenna

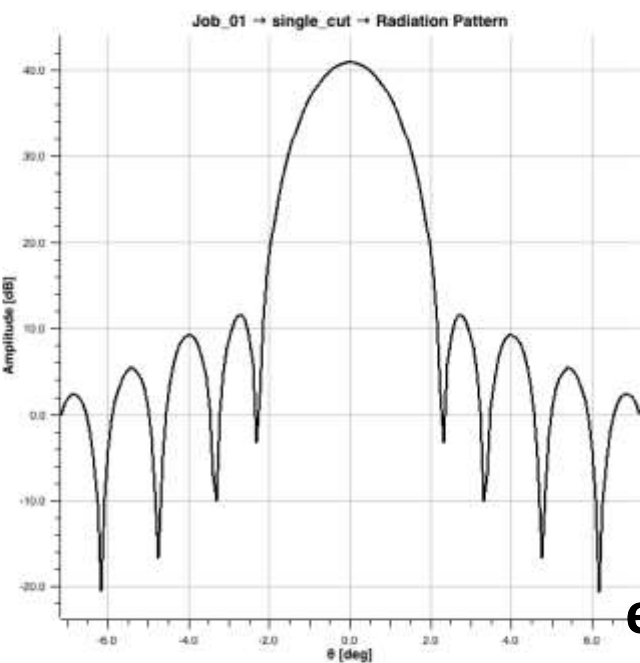
- **Spot beams are widely used in Ka band. Spot beams are created using multiple feeds with single or dual reflectors.**





Communication Satellites
Antenna

- **Parabolic antenna gain is calculated using efficiency, frequency and diameter. Antenna efficiency is the measure of an antenna's capability to convert the input power to the radiated power (typical value is 0.65).**
- **Gain unit is dBi, decibels relative to an isotropic antenna**
- **Directivity of antenna is calculated, gain of the antenna measured including efficiency or if efficiency is given we can calculate the gain. For n=0.65 there is -1.87dB difference, for n=0.8 difference is -1dB**



$$G = \eta \times \frac{4\pi A}{\lambda}$$

$$c = F \times \lambda, \eta = 0.65$$

$$F\ (Ghz), D\ (meter)$$

$$G = 20\log(F.D) + 18.53\ dBi$$

example: F=12Ghz, D=1m G=40.1 dBi

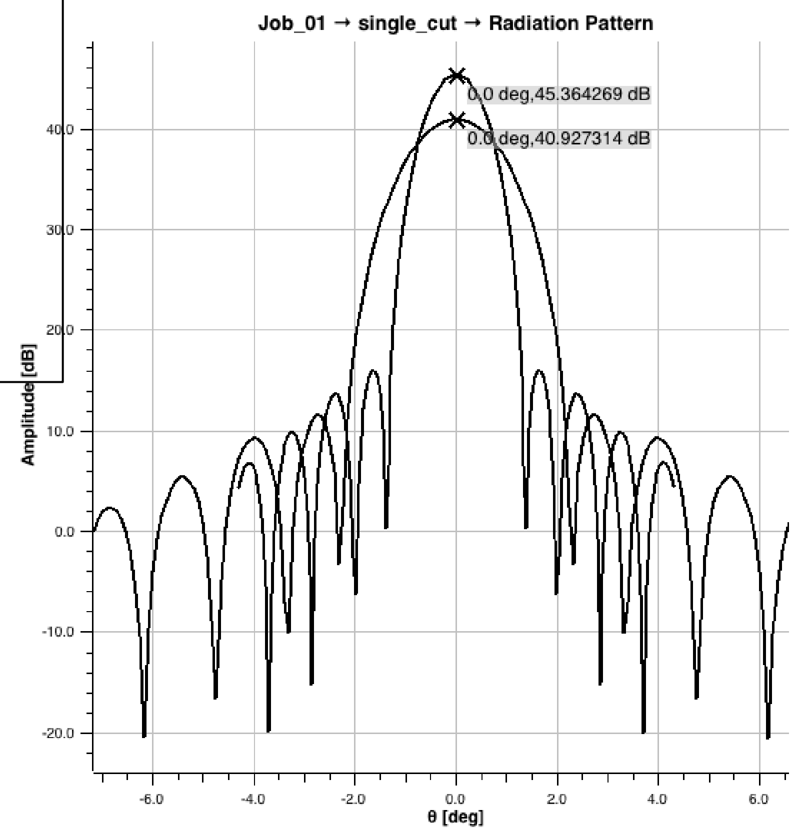
Communication Satellites
Antenna Gain Ka Band

- **Gain increases with higher frequencies such as Ka band at 20GHz**

F=20Ghz, D=1m

$$\boldsymbol{G = 20\log(F.D) + 18.53\ dBi}$$

G=20log(20x1)+18.53=44.5 dBi



Communication Satellites
3dB Beamwidth

- **3dB beamwidth of parabolic reflectors can be simplified as below. Notice that higher the frequency or diameter results narrow beamwidth.**

$$3dB = \frac{21}{f(GHz).D(m)}$$

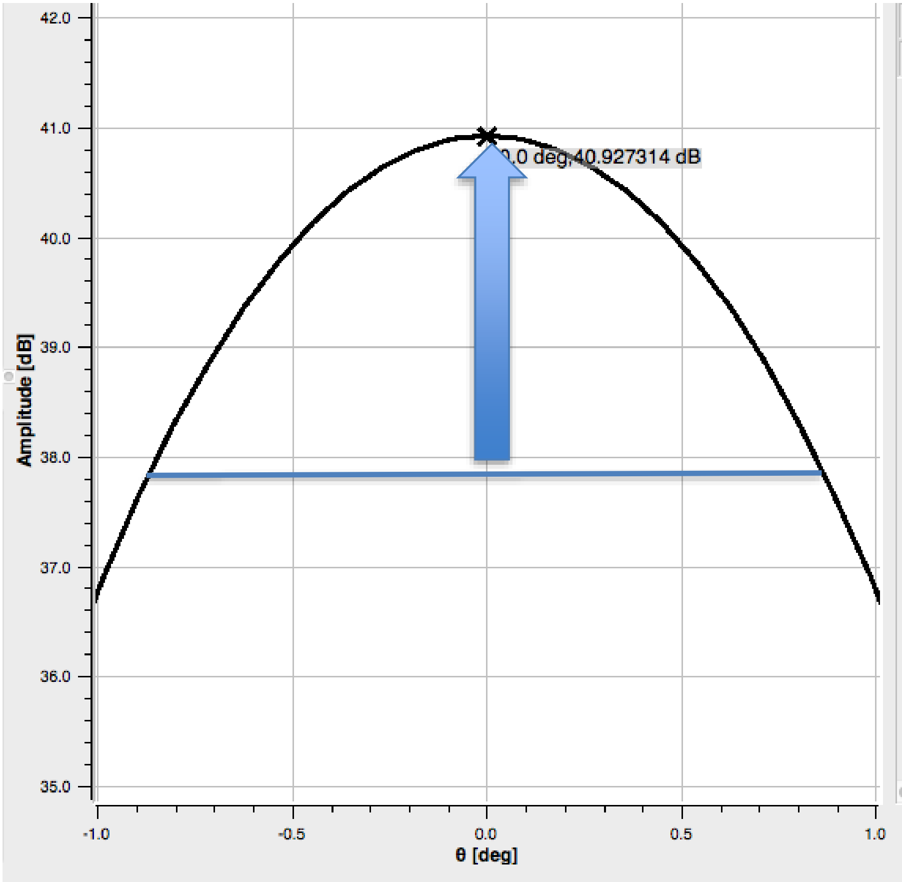
$$f = 12GHz, D = 1m$$

$$G = 10\log(\eta) + 20\log(f.D) + 20.4$$

$$G = 40.1dBi$$

$$3dB = 1.8^o$$

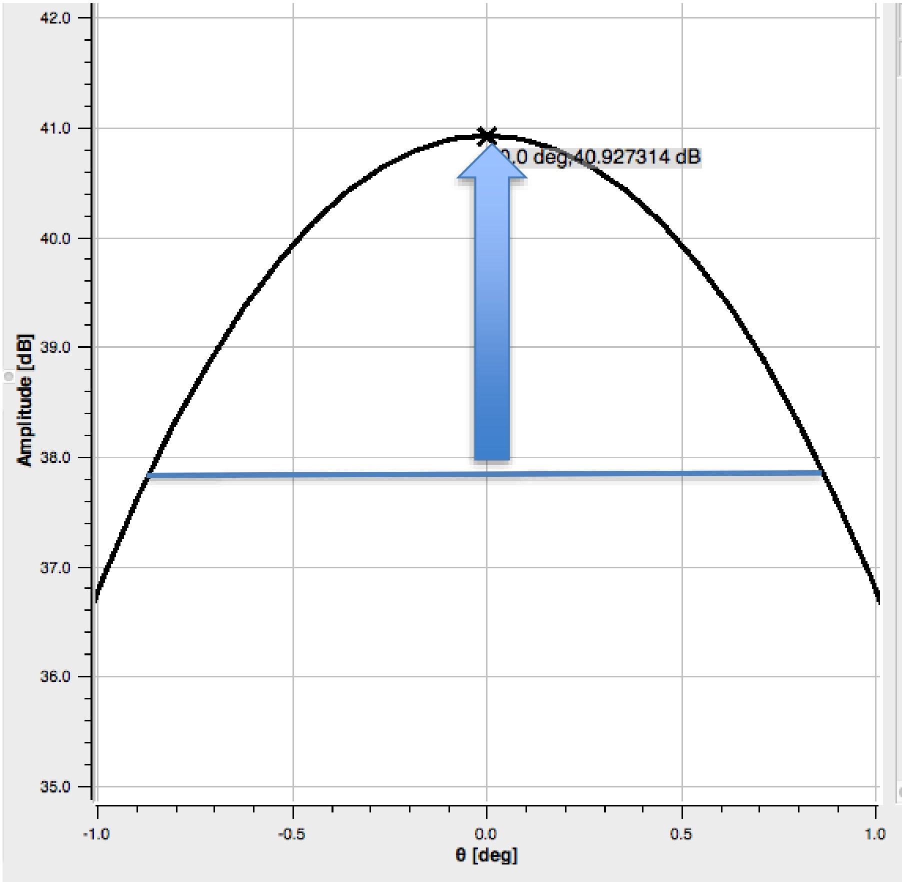
$$f = 20GHz \rightarrow 3dB = 1.1^o$$



Communication Satellites
3dB Beamwidth

- **3dB beamwidth of parabolic reflectors can be simplified as below. Notice that higher the frequency or diameter results narrow beamwidth.**

f	12	GHz
D	7	m
3db	0,25	deg



Communication Satellites
3dB Beamwidth

Beamwidth is a measure of the angle over which most of the gain occurs. It is typically defined with respect to the Half-Power Beamwidth (HPBW) or –3 dB points of the main lobe in the antenna radiation pattern. (See Figure 3.9.) It is given by:

$$\text{HPBW} = \frac{\lambda}{d\sqrt{\eta}} \times 57.29$$

$$\boxed{\theta_{3dB} = \frac{21}{F(Ghz).D(m)}}$$

Where:

- η= the antenna efficiency
- d= the antenna diameter in meters
- λ= the wavelength, c/f

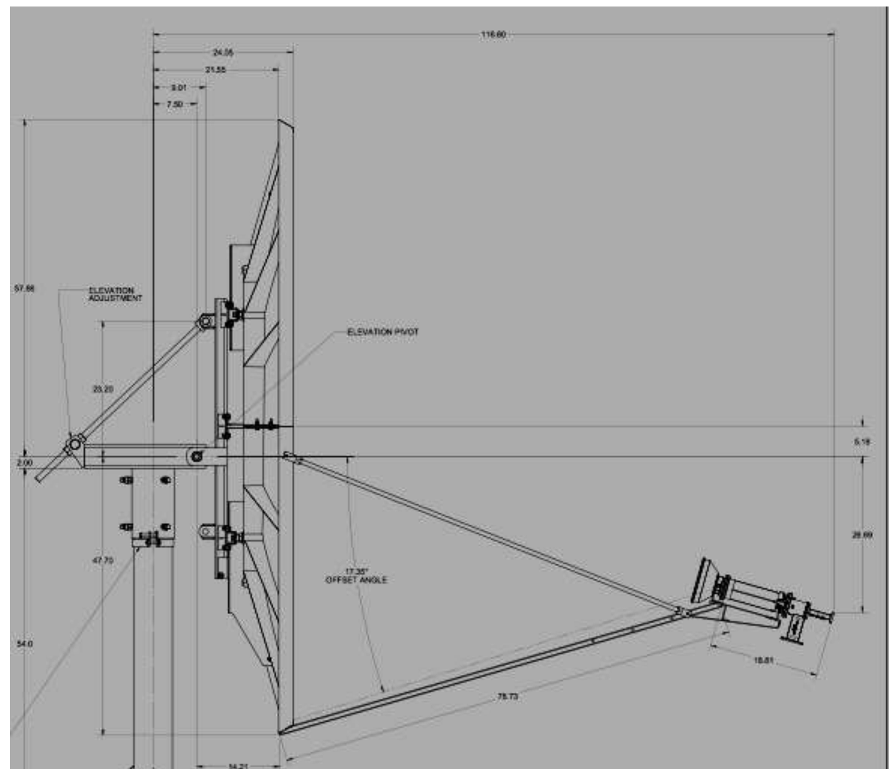
A standard "A" Earth station with an antenna of 16 meters (52 feet), and an efficiency of 70 percent would thus have a beamwidth of 0.214 degree at 6 GHz.

Communication Satellites
Antenna Software

- **TICRA’s Grasp antenna software student version is free.**
- **http://www.ticra.com/products/software/grasp/grasp-student-edition**

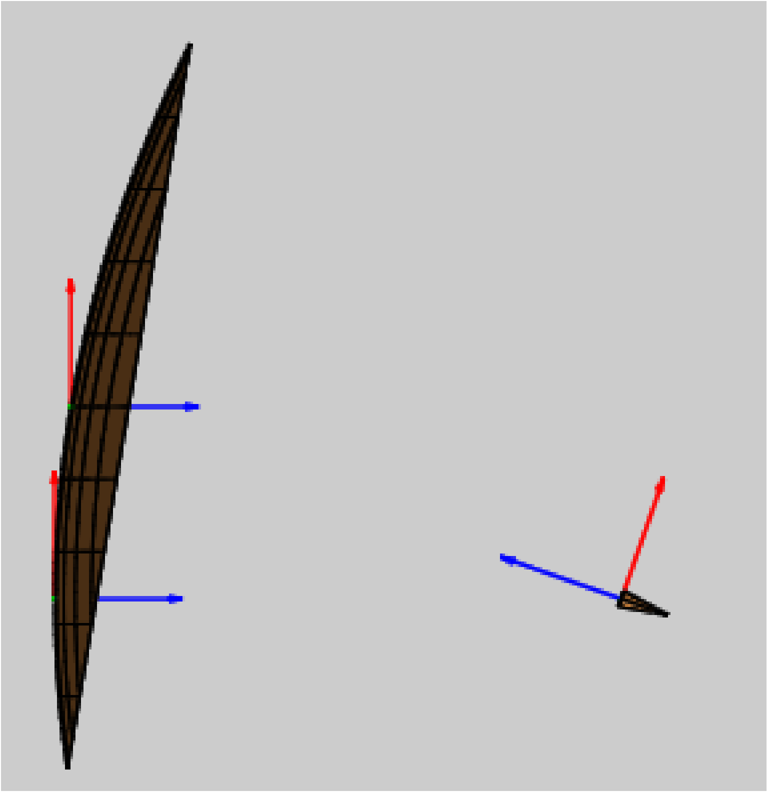
Communication Satellites
Single reflector Example

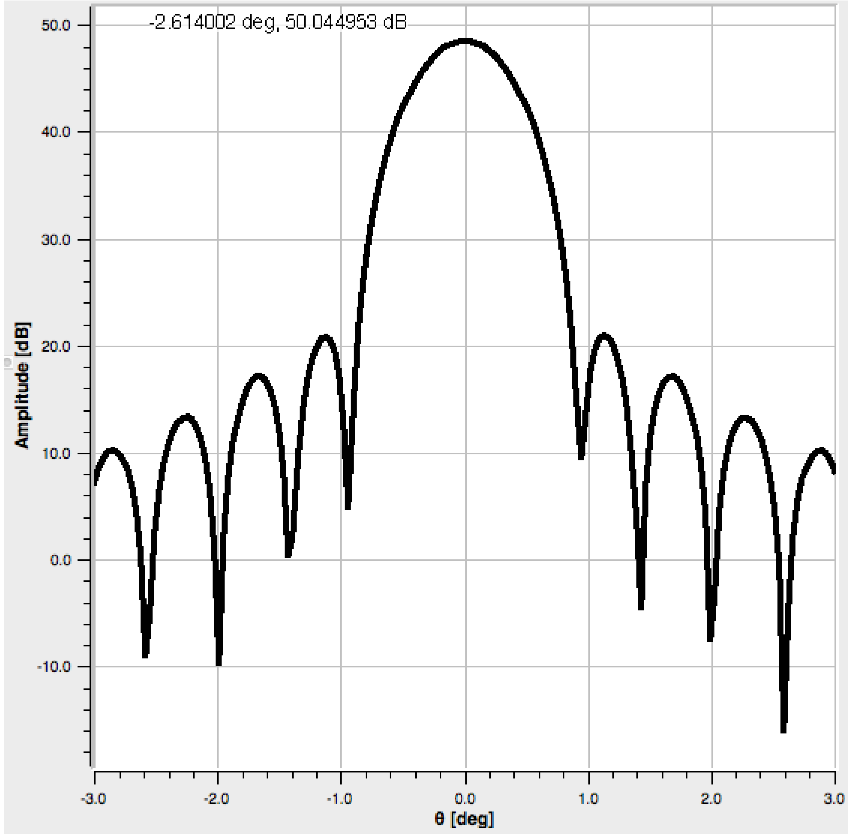
- **Antennas can be categorized into two group: single reflector, dual reflector**
- **Example 2.4m (100.58inch), Focal Length=79.73inch, 26.69inch offset (17.35 degree) single offset parabolic antenna, receive mid-frequency=11.725GHz (10.700-12.750GHz)**



Communication Satellites
Single reflector Example

- **Example 2.4m (96inch), Focal Length=79.73inch, 26.69inch offset (17.35 degree) single offset parabolic antenna, receive mid-frequency=11.725GHz (10.700-12.750GHz)**
- **Peak Directivity= 48.5dB, 3dB=0.75degree**





Frequency	7	GHz
Diameter	1,8	m
Gain	40,5	dBi
3db	1,67	deg

Tx Gain (mid-band) (dBi)	40.5 dBi @ 7.0 GHz
Rx Tx Gain (mid-band) (dBi)	37.3 dBi @ 4.8 Ghz

Antenna Size	1.8m

Communication Satellites
Single reflector Example

- **Example 2.4m (96inch), Focal Length=79.73inch, 26.69inch offset (17.35 degree) single offset parabolic antenna, receive mid-frequency=11.725GHz (10.700-12.750GHz)**
- **Peak Directivity= 48.5dBi (Gain including efficiency=47.4dBi), 3dB=0.7degree**

Electrical		C-Band Linear	C-Band Circular	Ku-Band
Antenna Size		2.4M (96 in.)	2.4M (96 in.)	2.4M (96 in.)
Operating Frequency (GHz)	Receive Transmit	3.625 - 4.20 GHz 5.85 - 6.425 GHz	3.625 - 4.20 GHz 5.85 - 6.425 GHz	10.70 - 12.75 GHz 13.75 - 14.50 GHz
Antenna Gain at Midband, dBi (± .2dB)	Receive Transmit	38.20 dBi 42.20 dBi	38.20 dBi 42.20 dBi	47.40 dBi 49.20 dBi
VSWR		1.3:1 Max	1.3:1 Max	Rx: 1.5:1 Max Tx: 1.3:1 Max
Pattern Beamwidth (in degrees at midband)	-3 dB -15 dB	Rx: 2.20° Tx: 1.40° Rx: 4.90° Tx: 3.10°	Rx: 2.20° Tx: 1.40° Rx: 4.90° Tx: 3.10°	Rx: 0.70° Tx: 0.60° Rx: 1.60° Tx: 1.40°

$$f = 11.725GHz, D = 2.4m, h = 0.65$$

$$3dB = \frac{21}{f(GHz).D(m)} = 0.7^{o}$$

$$G = 10\log(h) + (20\log(f.D) + 20.4 = 47.5dBi$$

Arrowe

Satmaster Pro Mk10.x Series

Overview

Satmaster Pro, is a tool mainly used for preparing satellite link budgets and predicting sun outage events. A demo version, with some limitations is available to download for evaluation.

Satmaster Pro Mk10.5a - DEMO - [GEO Link Budget - Untitled]

File Edit Map Graph Table Calculate Options Window Help

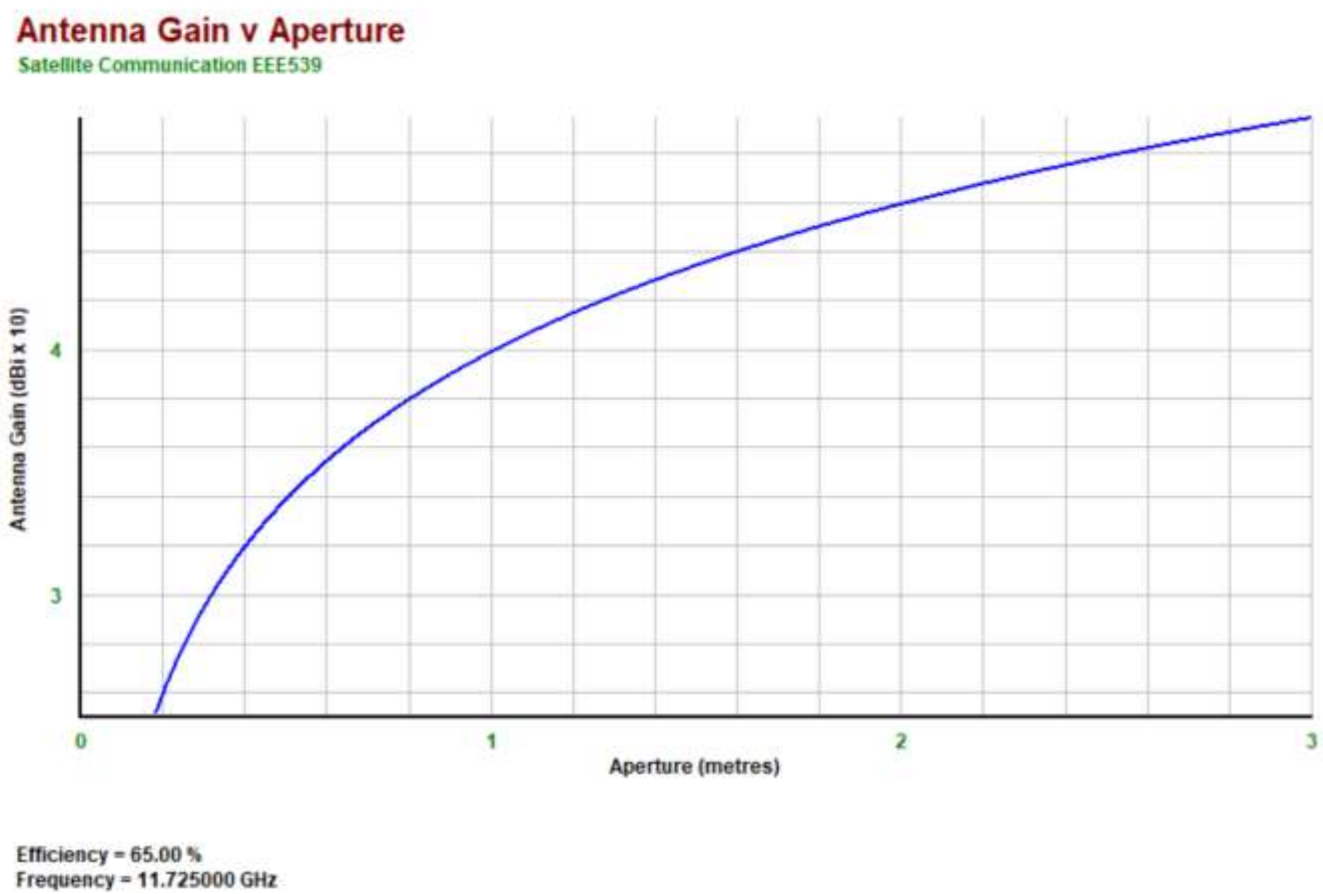
Flange transmit (up)	-55.02	-55.02	-55.02	dBW/Hz
Satellite (down)	-22.77	-22.77	-22.77	dBW/Hz
Satelite beam peak (down)	N/A	N/A	N/A	dBW/Hz
Flange receive (down)	-192.68	-192.68	-192.68	dBW/Hz

Earth Station Power Requirements	**Value**	**Units**
EIRP per carrier	72.58	dBW
Available uplink power control	0.00	dB
Total EIRP required	72.58	dBW
Antenna gain	52.82	dBi
Antenna feed flange power per carrier	19.75	dBW
HPA output back off	0.00	dB
Waveguide loss	0	dB
Number of HPA carriers	1	
Total HPA power required	19.7543	dBW
Required HPA power	94.4985	W

Space Segment Utilization	**Value**	**Units**
Overall target availability	N/A	%
Information rate	66.8430	Mbps
Information rate (inc overhead)	66.8430	Mbps
Transmit rate	90.0000	Mbps

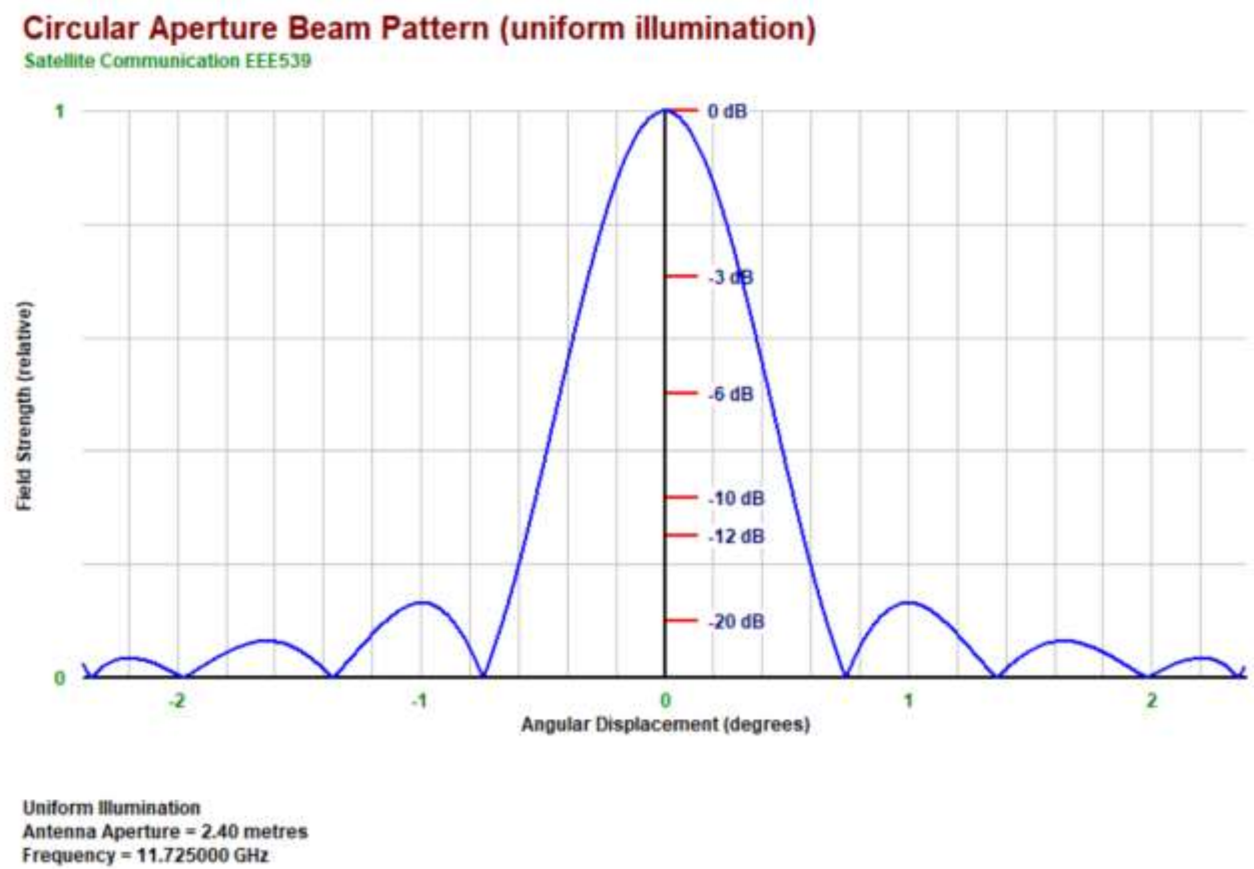
Satmaster Pro
Single reflector Example

- Example 2.4m fequency=11.725GHz
- Gain including efficiency=47.4dBi, 3dB=0.7degree



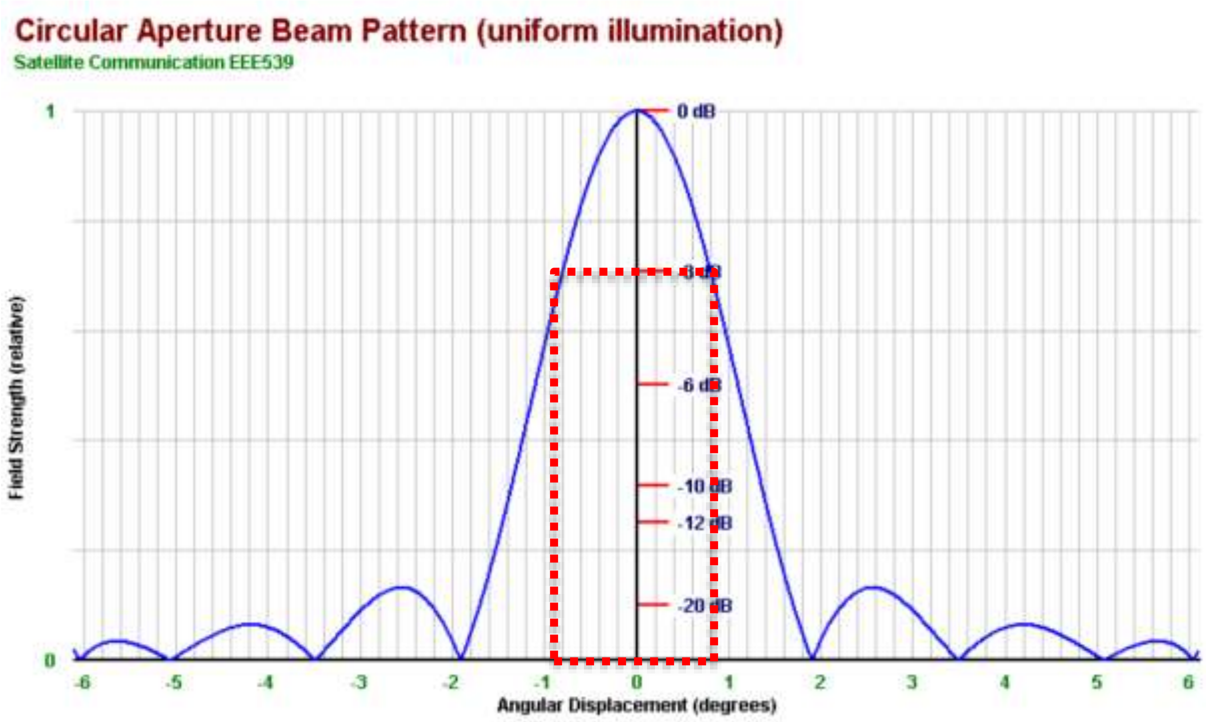
Satmaster Pro
Single reflector Example

- Example 2.4m fequency=11.725GHz
- Gain including efficiency=47.4dBi, 3dB=0.7degree



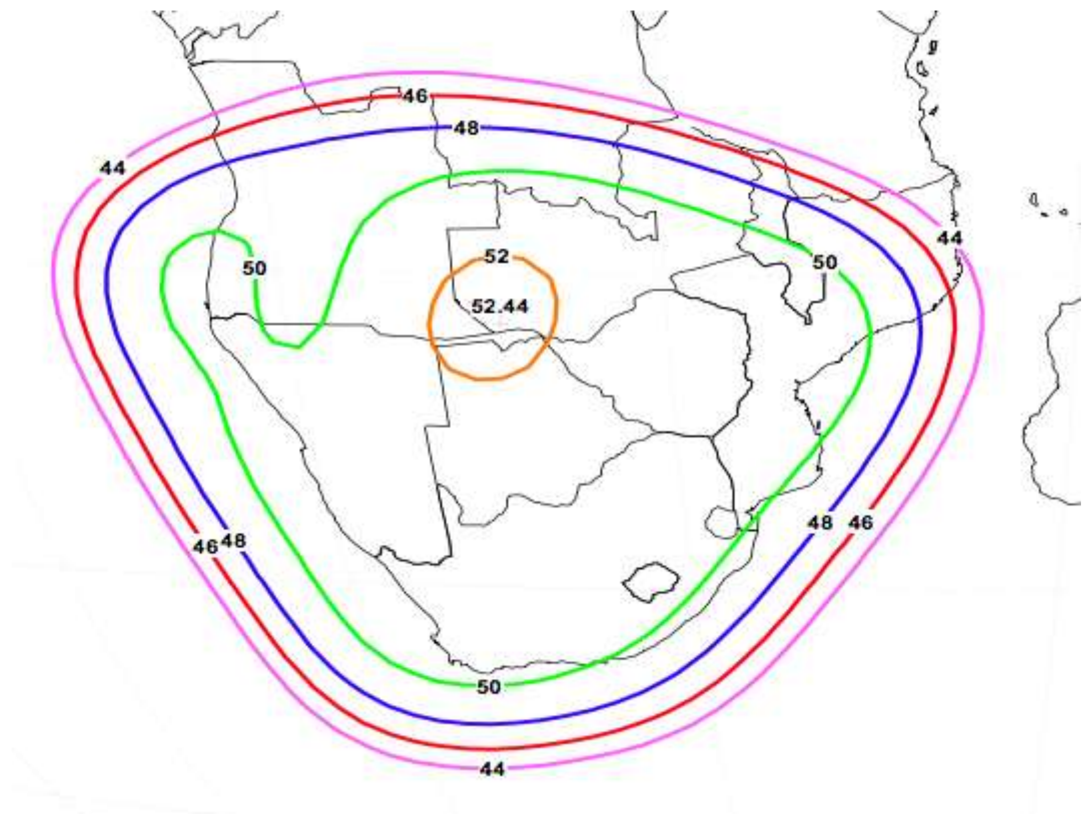
Satmaster Pro
Single reflector Example

- Example 1.8m fequency=6.1GHz
- Gain including efficiency=39.3dBi, 3dB=1.9degree



Communication Satellites
Coverage Maps-EIRP

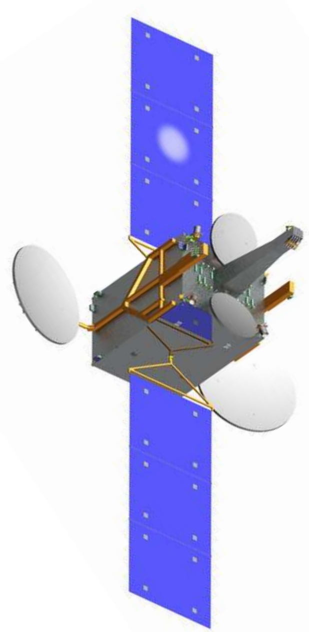
- **Satellite coverage maps shows EIRP pattern over Earth surface. Polygons or different colors distinguishes different EIRP levels**
- **What is EIRP ?**

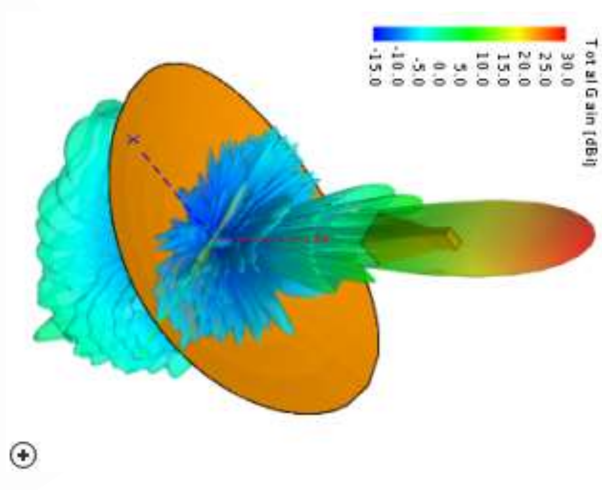


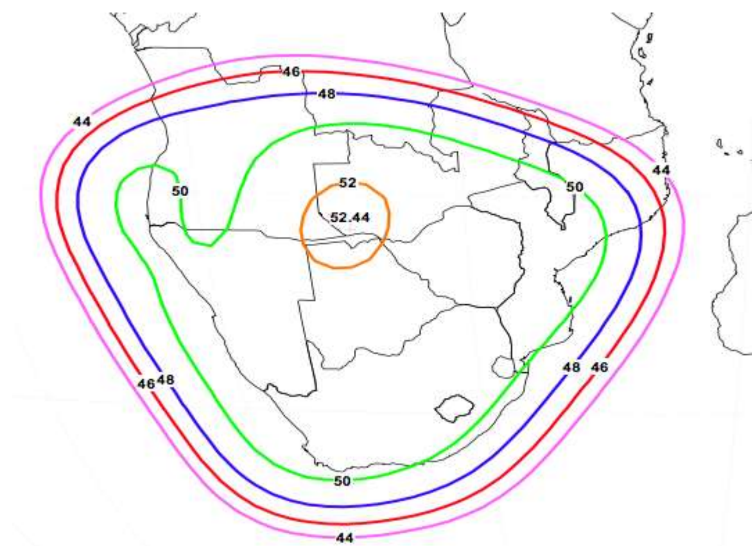
Communication Satellites
EIRP

- **EIRP is Equivalent Isotropic Radiated Power. EIRP is multiplication of transmit antenna power and gain. EIRP contours are intersection of antenna gain pattern and Earth Surface.**

$$EIRP = Power.Gain$$

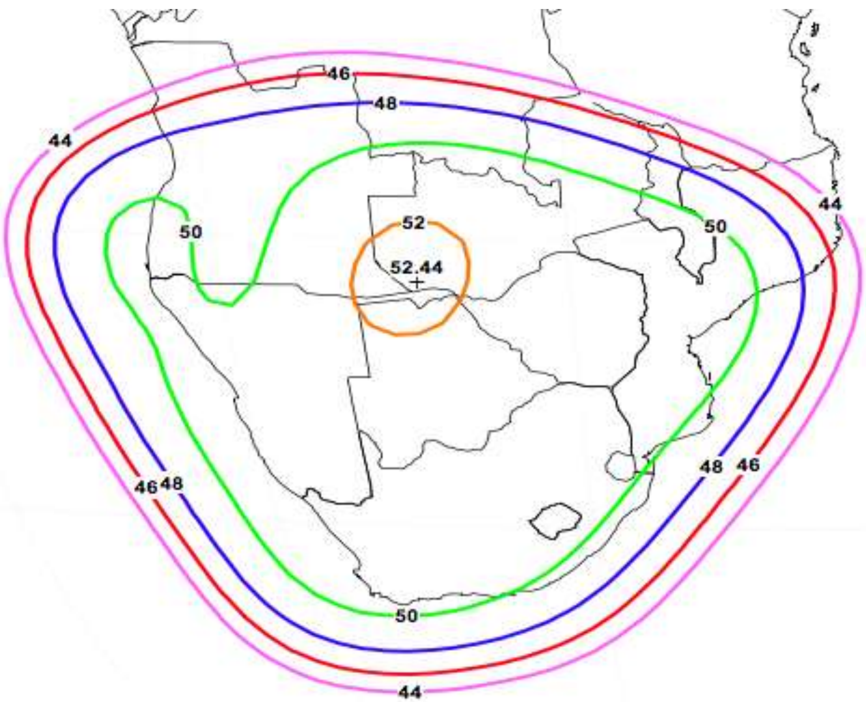


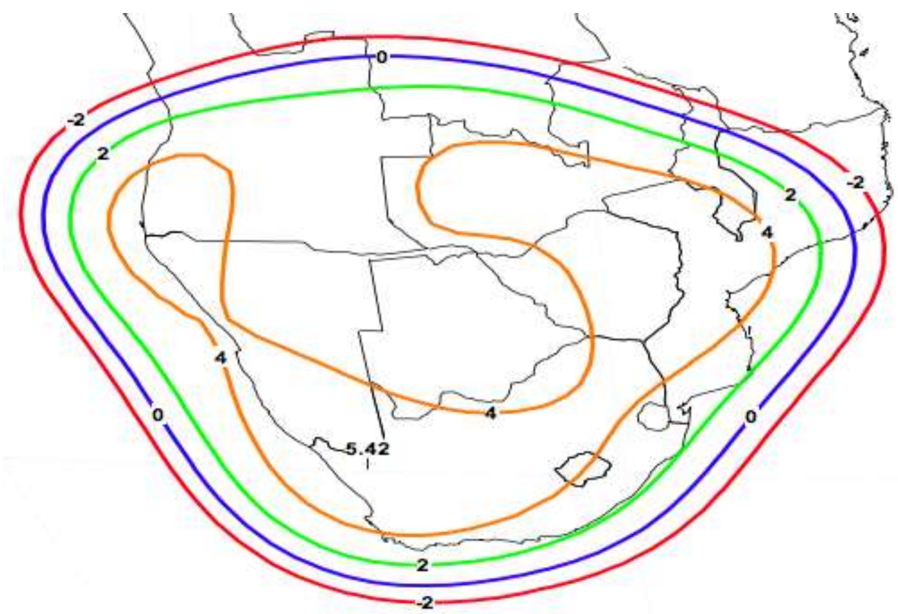




Communication Satellites
EIRP (transimission) vs G/T (reception)

- **While EIRP was providing downlink power of the satellite, G/T contours are also given to provide receive performance of the satellite antenna for the coverage area**



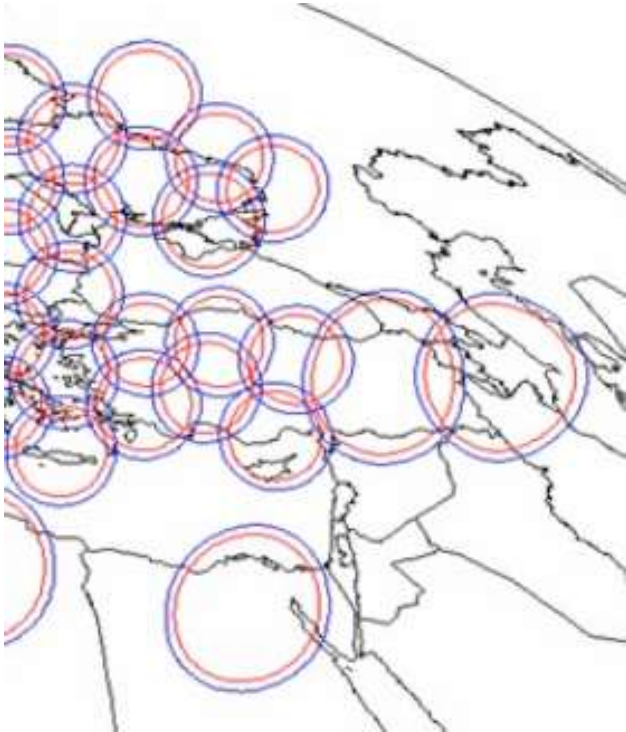


Communication Satellites
Ka band Spot Beam

- **1.6m satellite antenna provides 0.7 degree spot beams at 20GHz**

$$f = 20GHz, D = 1.6m$$

$$3dB = \frac{21}{f(GHz).D(m)} = 0.7^o$$

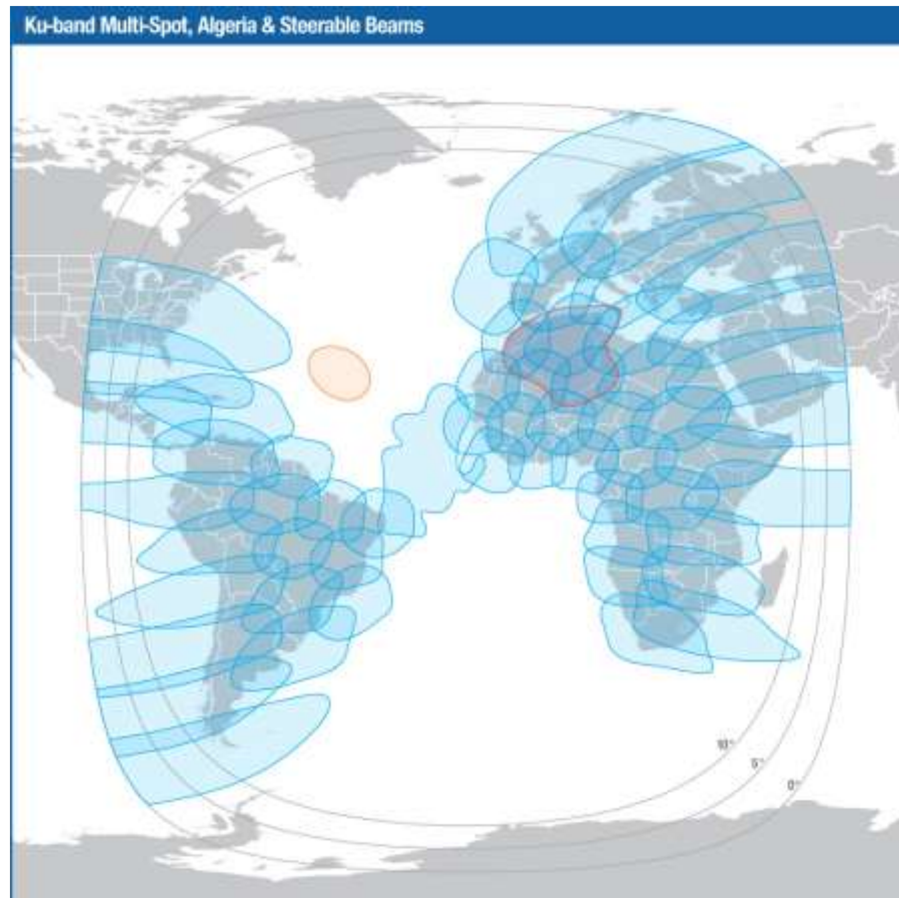


Communication Satellites
Ka band Spot Beam

- **1.6m satellite antenna provides 0.7 degree spot beams at 20GHz**

$$f = 20GHz, D = 1.6m$$

$$3dB = \frac{21}{f(GHz).D(m)} = 0.7^o$$



Communication Satellites
Ka band Spot Beam

- **3.5m satellite antenna, at Ka band 20Ghz has 0.3 degree 3dB beamwidth**

$$3dB = \frac{21}{F.D} = 0.3deg$$

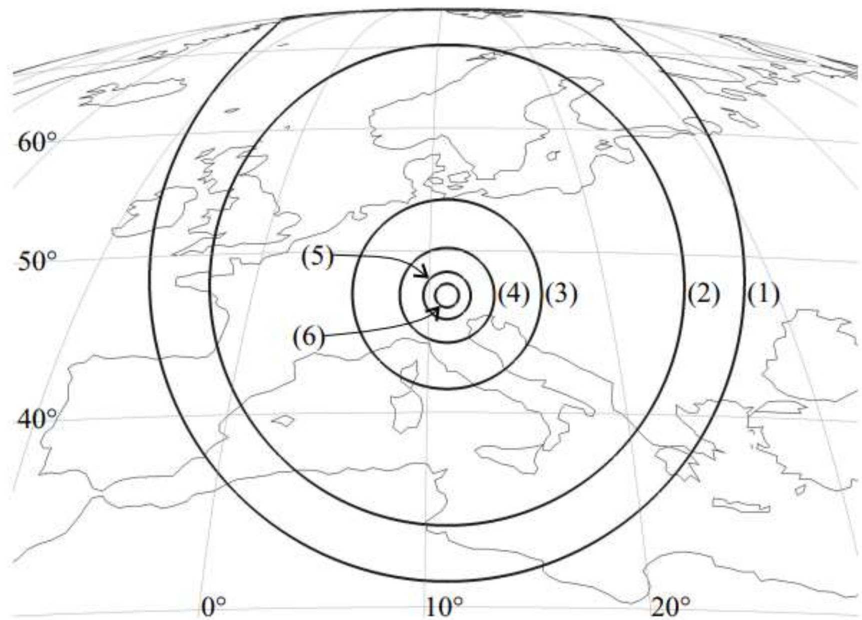


Figure 3.8: Comparison of spot beam size (3 dB below maximum contour is shown) for a GEO satellite at (11°East, 0°). Diameter of satellite antenna is $d_a = 3.5$ m, further $\eta_a = 0.6$. (1) $f = 1.6$ GHz, $\vartheta_{3dB} = 1.88°$, $G = 33.2$ dB; (2) $f = 2$ GHz, $\vartheta_{3dB} = 1.5°$, $G = 35.1$ dB; (3) $f = 5$ GHz, $\vartheta_{3dB} = 0.6°$, $G = 43$ dB; (4) $f = 10$ GHz, $\vartheta_{3dB} = 0.3°$, $G = 49.1$ dB; (5) $f = 20$ GHz, $\vartheta_{3dB} = 0.15°$, $G = 55.1$ dB; (6) $f = 40$ GHz, $\vartheta_{3dB} = 0.075°$, $G = 61.1$ dB.

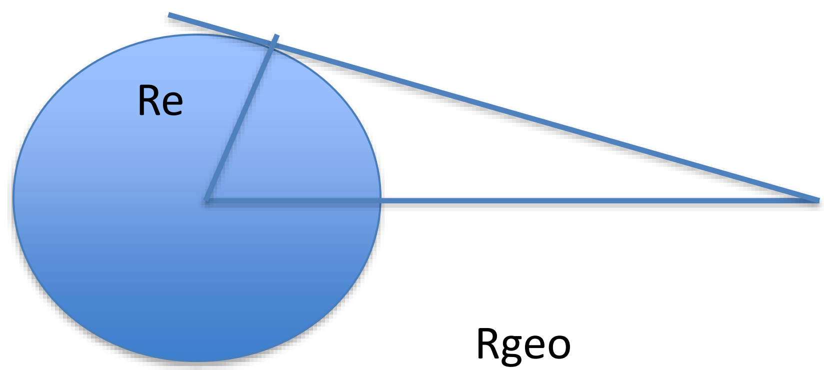
Communication Satellites
Earth from GEO Orbit

- Earth surface from geostationary orbit covers 2x8.7=17.4degree..

$$R_e = 6378km$$

$$R_{geo} = 42164km$$

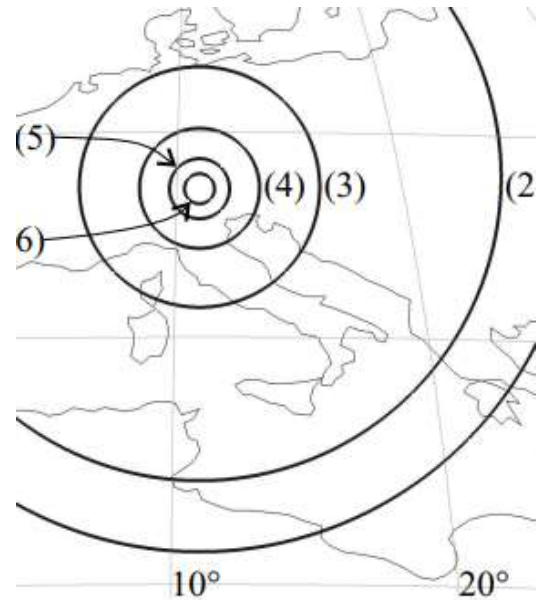
$$\alpha = a\sin(\frac{R_e}{R_{geo}}) = 8.7^o$$



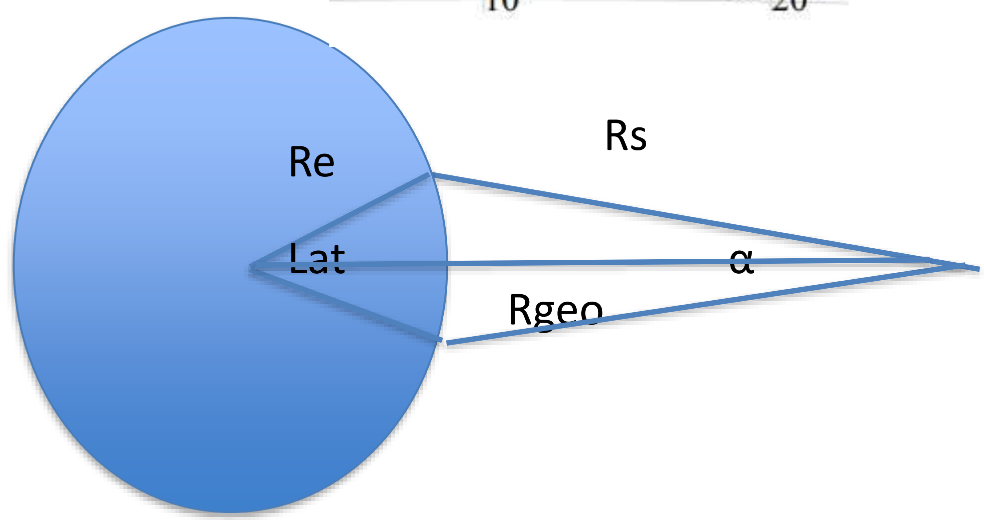
Communication Satellites
Earth from GEO Orbit

- Beam coverage on Earth depends on Latitude.

$$Re = 6378, Rgeo = 42164km, Rsat = 35786km$$
$$Re \times sin\left(\frac{Lat}{2}\right) = \mathrm{Rs} \times \sin\left(\frac{\alpha}{2}\right)$$
$$Lat = \arcsin\left\{2 \times \left(\frac{Rs}{Re}\right) \sin\left(\frac{\alpha}{2}\right)\right\}$$

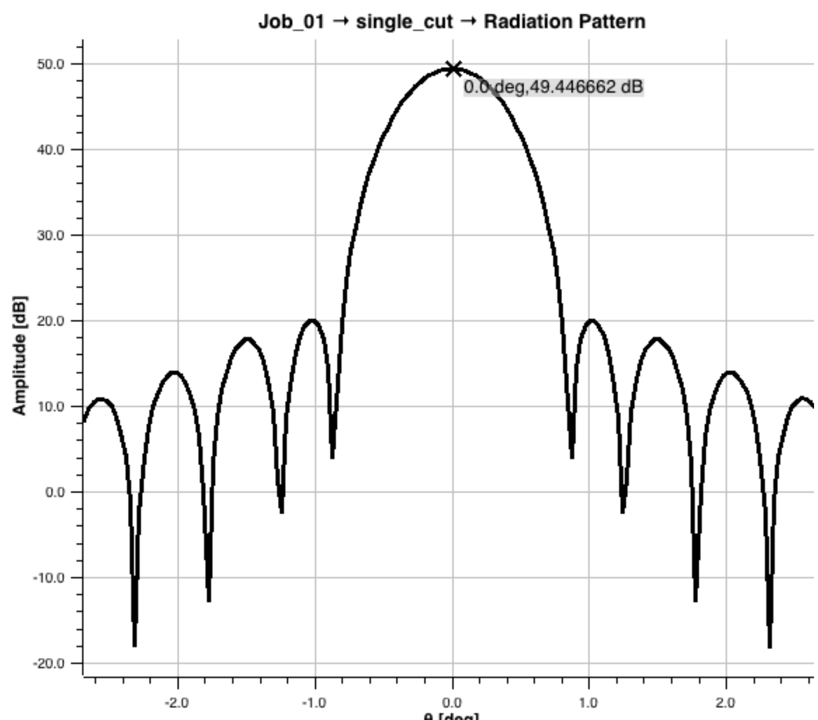


$5Ghz, 3.5m\ satellite\ antenna$
$3dB = 1.2°$, Lat=13.6°



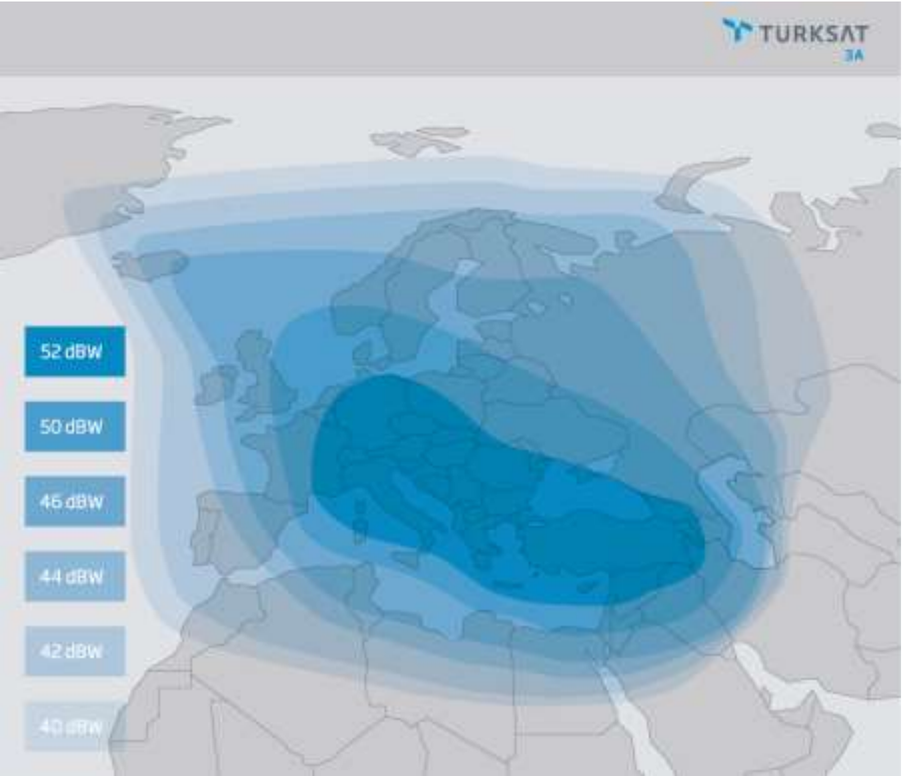
Communication Satellites
Pointing Error

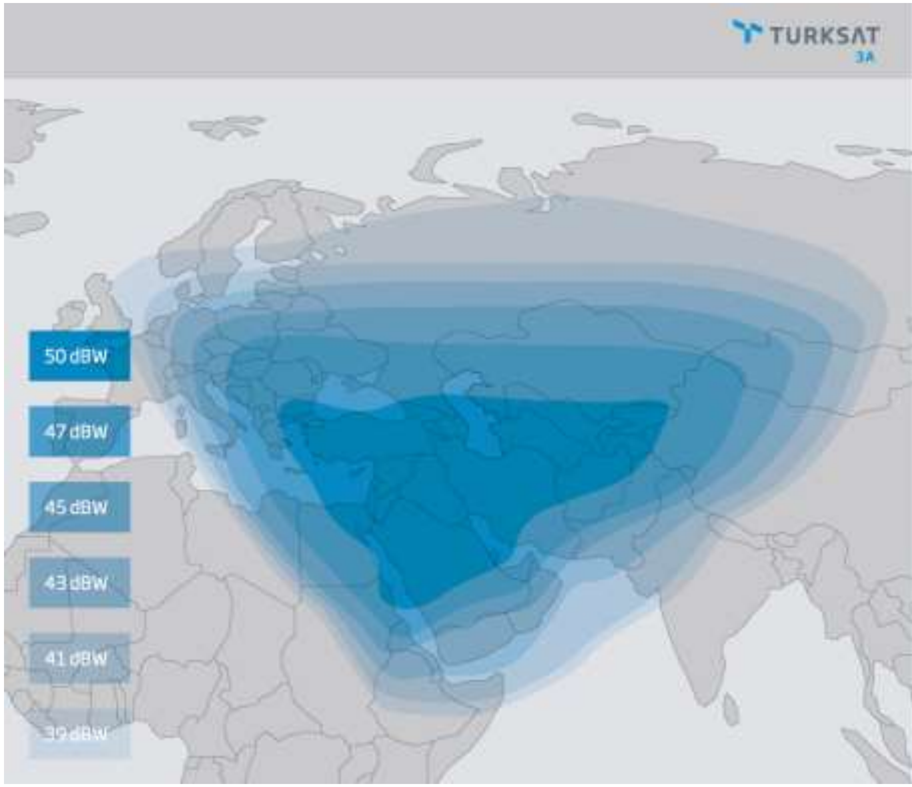
- **Pointing error is calculated using radiation pattern of the antenna. Narrower the beamwidth is pointing error is higher.**
- **Example 1.6m 20Ghz has directivity of 49.4dBi and 0.5degree error decreases antenna gain around 8dB**



Communication Satellites
Turksat Satellites

- **The first communication satellite of Turkey Turksat-1B launched in 1994.**
- **Turksat has three operation satellites: Turksat-3A, Turksat-4A at 42° East and Turksat-4B at 50° East**
- **Turksat coverage areas include Europe, Turkey, Middle East and Asia.**
- **Turksat-4B has Ka-band spot beams for data communication**





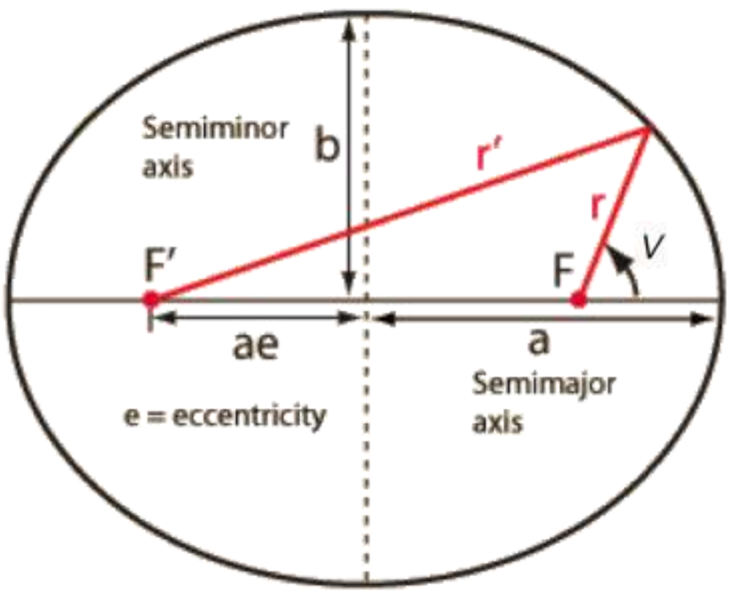
Satellite Orbits
Kepler's Laws

Kepler observed that the trajectories of planets around the sun were ellipses:

1. The planets move in a plane; the orbits described are ellipses with the sun at one focus (1602).
2. The vector from the sun to the planet sweeps equal areas in equal times (the law of areas,1605).
3. The ratio of the square of the period T of revolution of a planet around the sun to the cube of the semi-major axis a of the ellipse is the same for all planets (1618).

Satellite Orbits
Kepler's Law-1

The planets move on a plane; the orbits described are ellipses with the sun at one focus (1602).



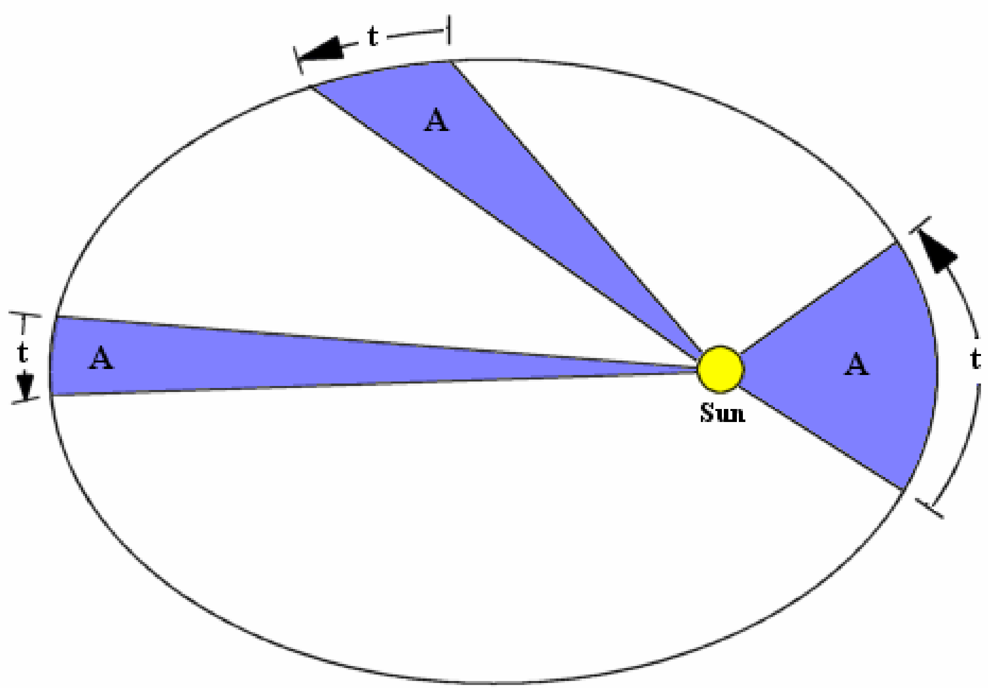
$$\frac{x^2}{a^2}+\frac{y^2}{b^2}=1\,(Cartesien)$$

$$r=\frac{a(1-e^2)}{1+e\cos(v)}\,(Polar)$$

$$e=\sqrt{1-\frac{b^2}{a^2}}$$

Satellite Orbits
Kepler's Law-2

The vector from the sun to the planet sweeps equal areas in equal times (the law of areas, 1605).



Satellite Orbits
Kepler's Law-2

The ratio of the square of the period T of revolution of a planet around the sun to the cube of the semi-major axis a of the ellipse is the same for all planets (1618). (How semimajor axis measured)

$$\frac{T^2}{a^3} = k$$

$$\boxed{\mathbf{T^2 = k \,.\, a^3}}$$

Satellite Orbits
Newton’s Law of Gravity

In 1687, Newton formulated law of gravity in his book Principia.

$$F = \frac{GMm}{R^2}$$

$$G = 6.6726 \text{x} 10^{-11}\ \text{Nm}^2/\text{kg}^2$$

$$GM = m = 398600.4418\ \text{km}^3/\text{s}^2$$

Satellite Orbits
Newton's Law of Gravity

Kepler's equations are based on observations. Newton's law mathematically can reach the same equations and solve any type of gravity problems.

$$F = \frac{GMm}{R^2} = \frac{mV^2}{R} \; (circular\ orbits)$$

$$V = \sqrt{\frac{GM}{R}}$$

$$V = \frac{2\pi R}{T} \Rightarrow \; T = 2\pi\sqrt{\frac{R^3}{GM}} \; (circular\ orbits)$$

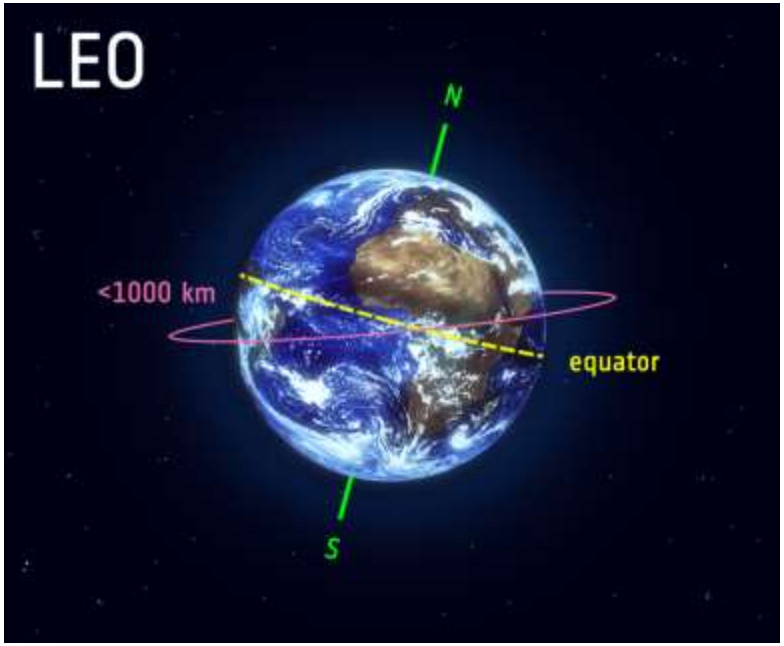
$$T = 2\pi\sqrt{\frac{a^3}{GM}} \; (all\ orbits)$$

Satellite Orbits

- Low Earth orbit (LEO)
- Medium Earth orbit (MEO)
- Geostationary orbit (GEO)

Low Earth orbit (LEO)

A low Earth orbit (LEO) is, as the name suggests, an orbit that is relatively close to Earth's surface. It is normally at an altitude of less than 1000 km but could be as low as 160 km above Earth – which is low compared to other orbits, but still very far above Earth's surface.

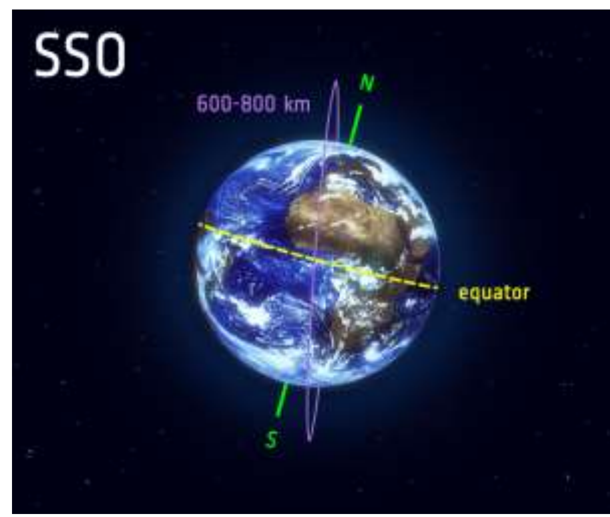


Satellite Orbits

- Low Earth orbit (LEO)
- Medium Earth orbit (MEO)
- Geostationary orbit (GEO)

Polar orbit and Sun-synchronous orbit (SSO)
Satellites in polar orbits usually travel past Earth from north to south rather than from west to east, passing roughly over Earth's poles.

Satellites in a polar orbit do not have to pass the North and South Pole precisely; even a deviation within 20 to 30 degrees is still classed as a polar orbit. Polar orbits are a type of low Earth orbit, as they are at low altitudes between 200 to 1000 km

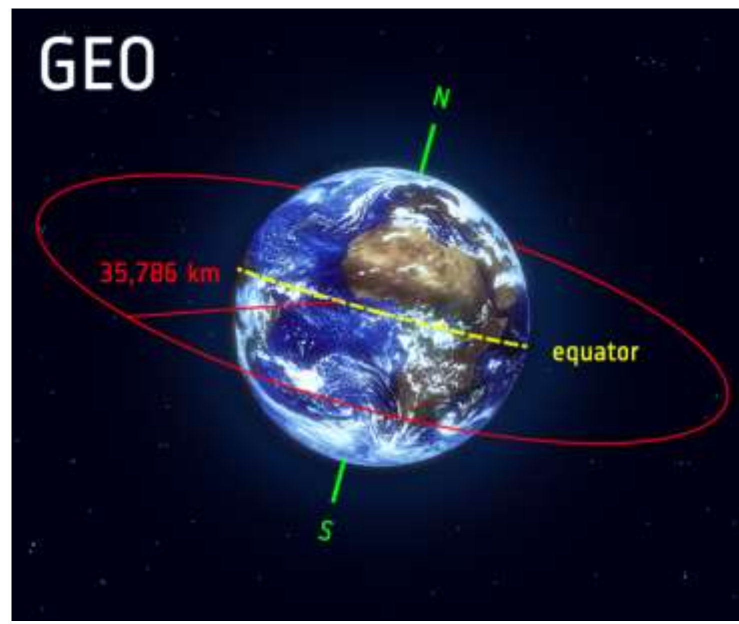


Satellite Orbits

- Low Earth orbit (LEO)
- Medium Earth orbit (MEO)
- Geostationary orbit (GEO)

Geostationary orbit (GEO)

Satellites in geostationary orbit (GEO) circle Earth above the equator from west to east following Earth's rotation – taking 23 hours 56 minutes and 4 seconds – by travelling at exactly the same rate as Earth. This makes satellites in GEO appear to be 'stationary' over a fixed position. In order to perfectly match Earth's rotation, the speed of GEO satellites should be about 3 km per second at an altitude of 35 786 km. This is much farther from Earth's surface compared to many satellites.

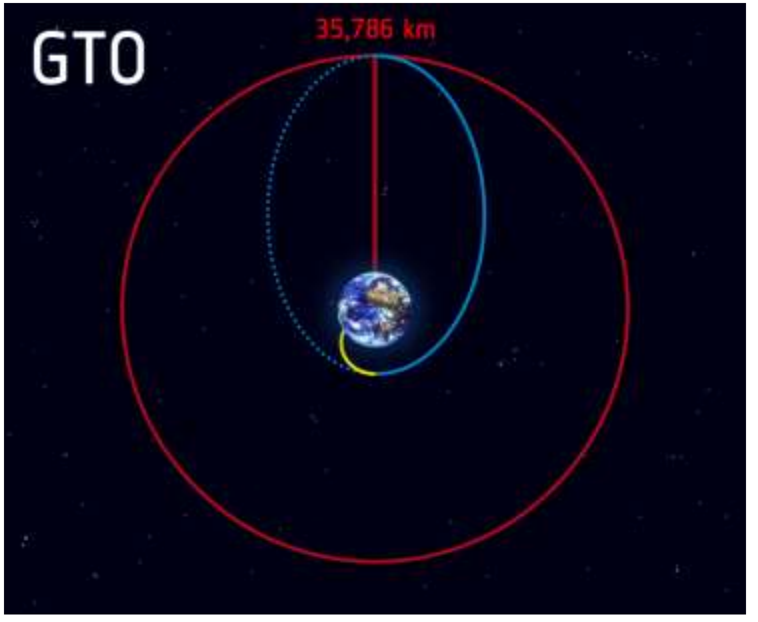


Satellite Orbits

- Low Earth orbit (LEO)
- Medium Earth orbit (MEO)
- Geostationary orbit (GEO)

Transfer orbits and geostationary transfer orbit (GTO)

Transfer orbits are a special kind of orbit used to get from one orbit to another. When satellites are launched from Earth and carried to space with launch vehicles such as Ariane 5, the satellites are not always placed directly on their final orbit. Often, the satellites are instead placed on a transfer orbit: an orbit where, by using relatively little energy from built-in motors, the satellite or spacecraft can move from one orbit to another.



Satellite Orbits

- Low Earth orbit (LEO)
- Medium Earth orbit (MEO)
- Geostationary orbit (GEO)

Medium Earth orbit (MEO)
Medium Earth orbit comprises a wide range of orbits anywhere between LEO and GEO. It is similar to LEO in that it also does not need to take specific paths around Earth, and it is used by a variety of satellites with many different applications.

Satellite Orbits
Low Earth Orbit Period

Gokturk-2's altitude (distance from Earth surface) is 686 km. The period is 98 minutes.

$$R_E = 6378\, km$$

$$a = 686 + 6378 = 7064\, km$$

$$T = 2p\sqrt{\frac{a^3}{GM}} = 98\,\mathrm{min}$$

$$V_S = \sqrt{\frac{GM}{a}} = 8 km / s$$

Satellite Orbits
Geostationary Orbit

What happens if the satellite period is equal to Earth rotation period, 23 hours, 56 minutes, 4 seconds = 86164 seconds ? **Arthur Clarke** noticed the commercial application at this “geostationary” orbit, in 1945.

$$T = 2p\sqrt{\frac{a^3}{GM}} = 86164\ s$$

$$a = 42164\ km$$

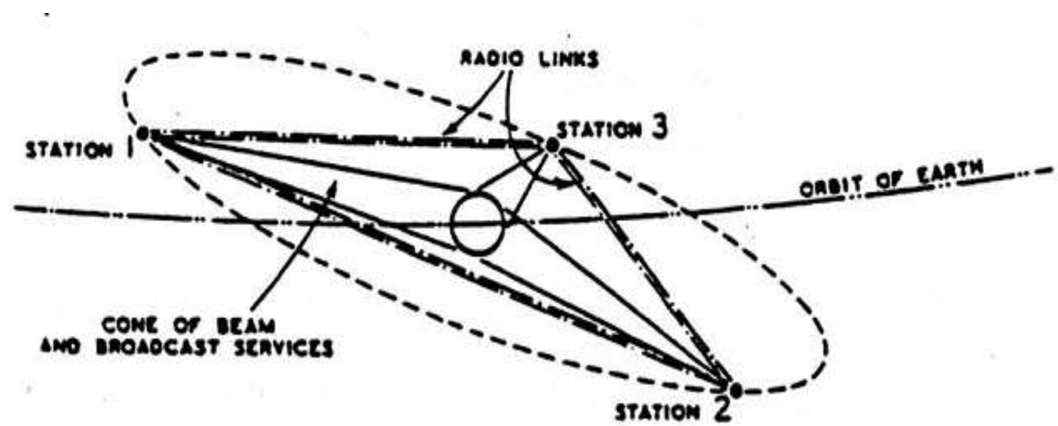


Fig. 3. Three satellite stations would ensure complete coverage of the globe.

Satellite Orbits
Geostationary Orbit Period

Earth radius 6378 km. Thus geostationary satellites are 35786 km far from the Earth surface. Satellite velocity is 3 km/s !!!

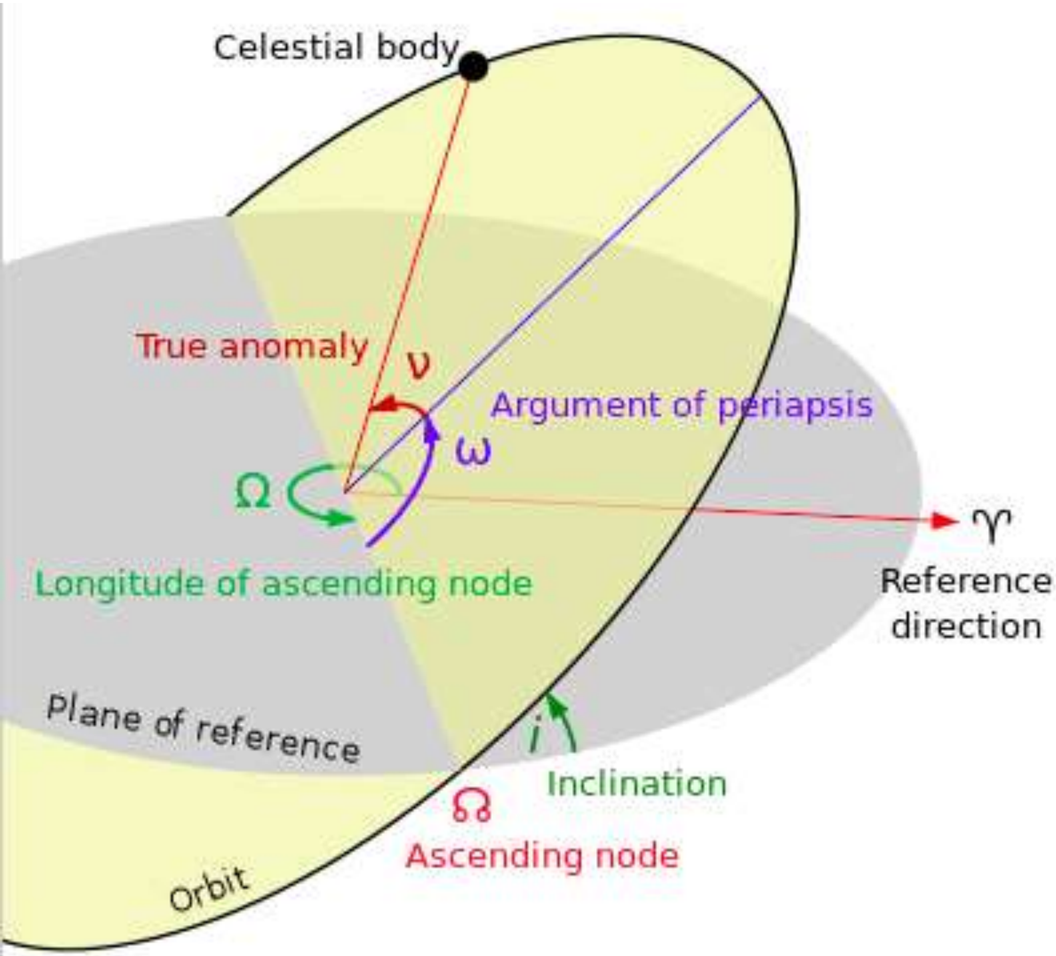
$$a = 42164\ km$$

$$R_E = 6378\ km$$

$$R_S = 35786\ km$$

$$V_S = \sqrt{\frac{GM}{a}} = 3\ km / s$$

Satellite Orbits
Orbital Elements

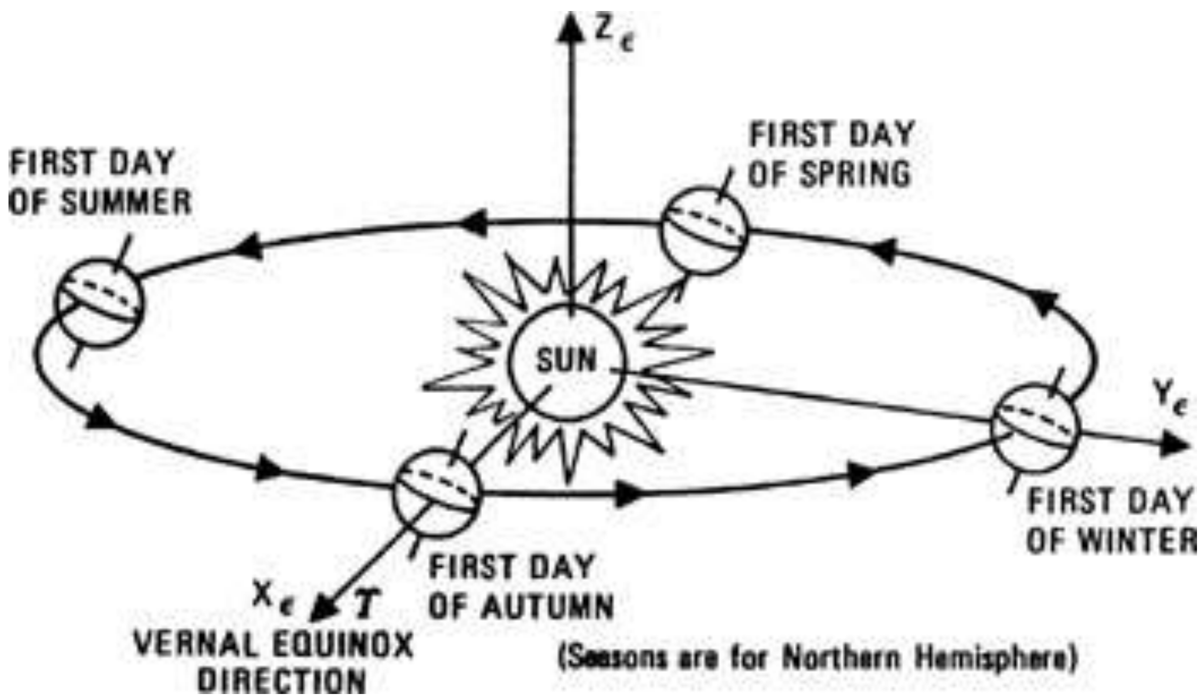


Satellite orbits can be defined using 6 parameters:

1. **a: semi major axis**
2. **e: eccentricity**
3. **i: inclination: angle between equatorial and orbit planes**
4. **True anomaly: angle from perigee**
5. **Right Ascension (longitude) of the ascending node: reference from Vernal Equinox**
6. **Argument of perigee: angle from ascending node to perigee**

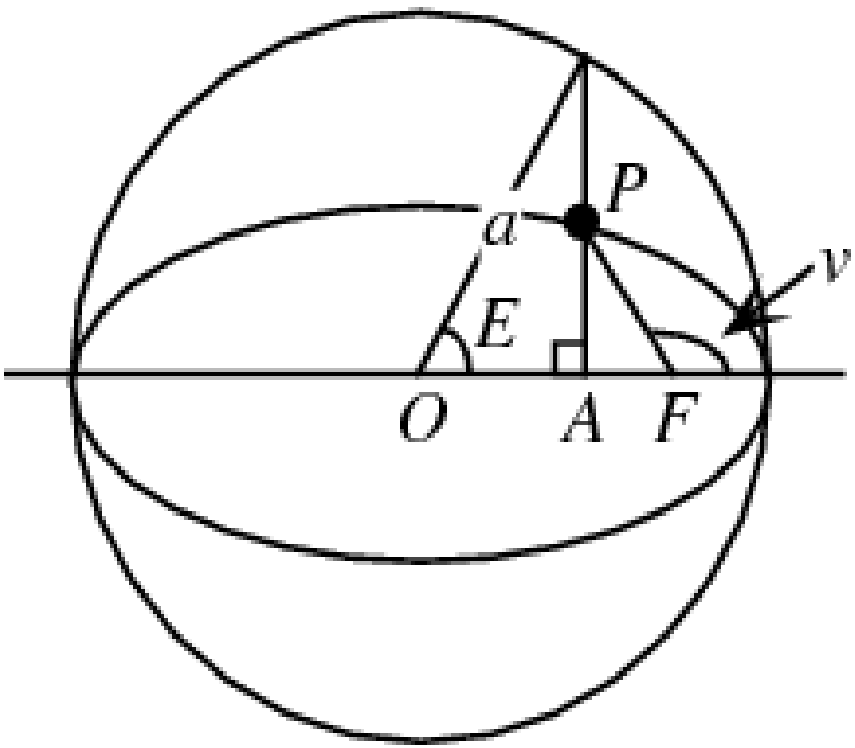
Satellite Orbits
Vernal Equinox

The vernal equinox is an imaginary point in space which lies along the line representing the intersection of the Earth's equatorial plane and the plane of the Earth's orbit around the Sun or the *ecliptic*



Satellite Orbits
Eccentric Anomaly and True Anomaly

- "P" is the point on elliptic orbit and **"v" is the True anomaly** angle from the A focal point
- Draw an auxiliary circle with a radius of semi major axis "a"
- **Eccentric anomaly (E)** is the angle from the center of axis



$$OF = ae$$

$$AF = OF - OA = ae - a\cos(E)$$

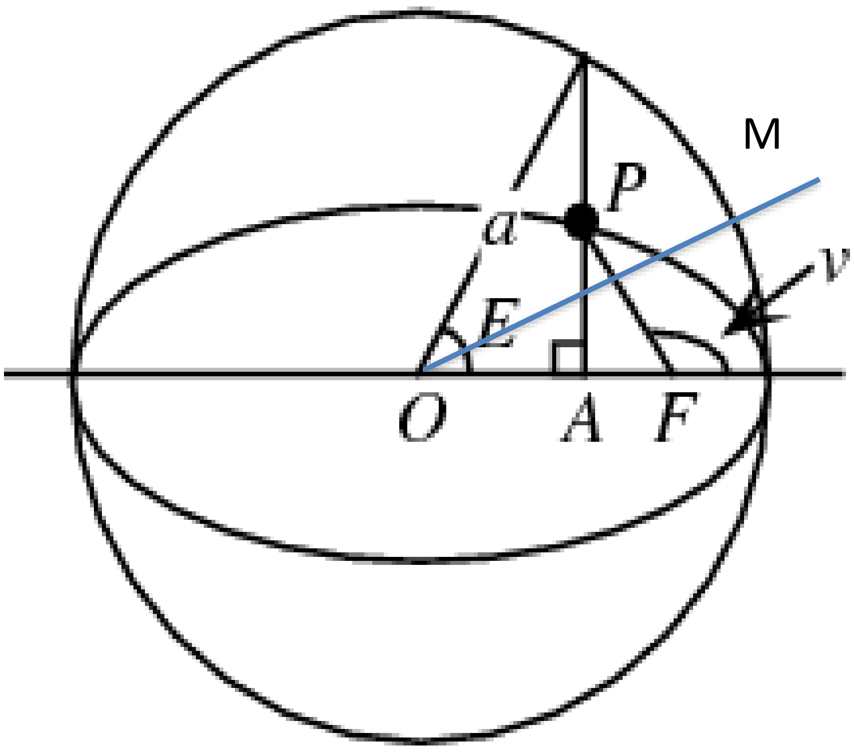
$$r = \frac{a(1-e^2)}{1+e\cos(v)}$$

$$\cos(u) = \frac{-AF}{r} = \frac{(\cos(E)-e)(1+e\cos(v))}{(1-e^2)}$$

$$\cos(v) = \frac{\cos(E)-e}{1-e\cos(E)}$$

Satellite Orbits
Kepler's Equation

Mean anomaly is the angle as if the satellite has a circular orbit with the same period.
We can calculate True anomaly (v) in time using Kepler's equation.



$$M = t\frac{360^o}{T}$$

$$M = E - eSin(E)$$

$$\cos(u) = \frac{\cos(E) - e}{1 - e\cos(E)}$$

$$r = \frac{a(1 - e^2)}{1 + e\cos(v)}$$

Satellite Orbits
Kepler's Equation Solution

1. Given time, Calculate M
2. Calculate E using Newton Raphson
3. Calculate v and r

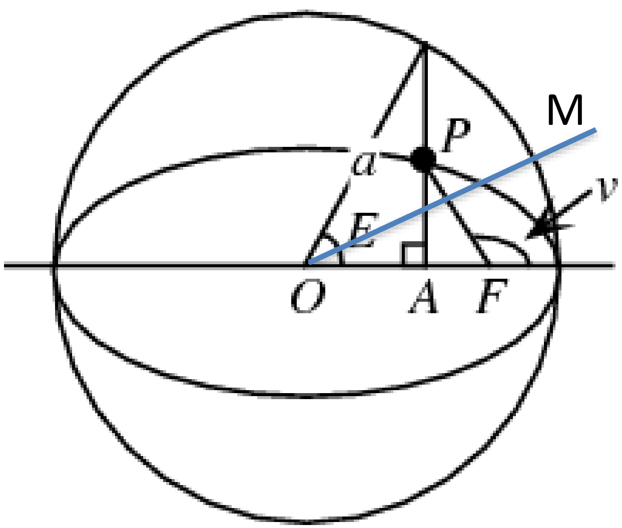
$$M = t\frac{360^o}{T}$$

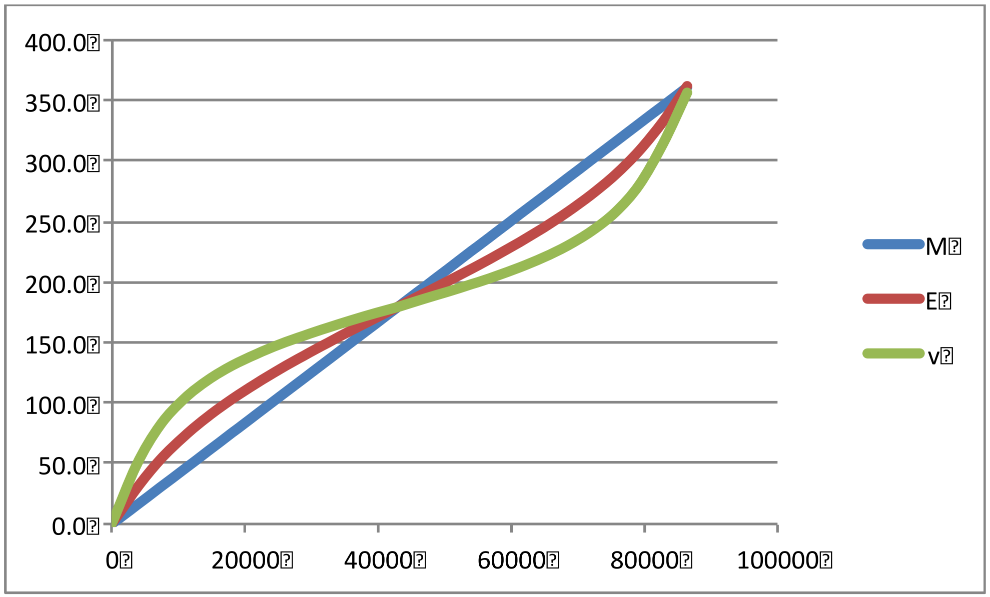
$$M = E - eSin(E)$$

$$\cos(u) = \frac{\cos(E) - e}{1 - e\cos(E)}$$

$$r = \frac{a(1 - e^2)}{1 + e\cos(v)}$$

Example graph with e=0.5,T=86164s. We can observe that three angles becomes equal at 0,180 degrees.

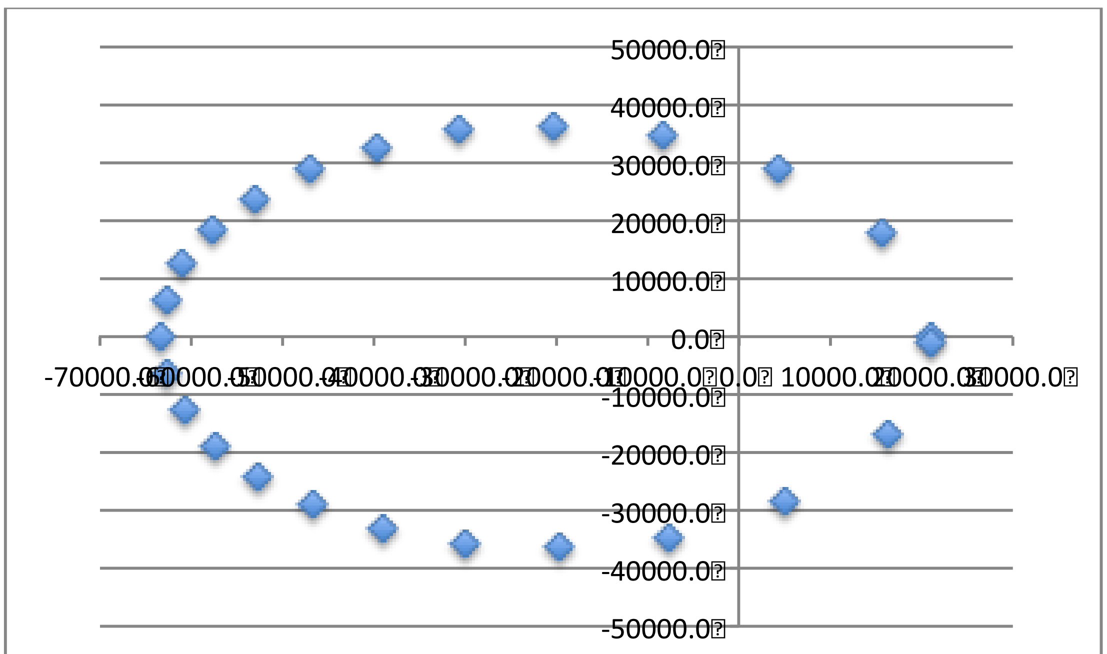




Satellite Orbits
Kepler's Equation Solution

1. Given time, Calculate M
2. Calculate E using Newton Raphson
3. Calculate v and r

Example graph with e=0.5,T=86164s (Dt=1hr).
We can observe perigee and apogee velocities



$$M = t\frac{360^o}{T}$$

$$M = E - eSin(E)$$

$$\cos(u) = \frac{\cos(E) - e}{1 - e\cos(E)}$$

$$r = \frac{a(1 - e^2)}{1 + e\cos(v)}$$

Satellite Orbits
Kepler's Equation Inverse Solution

By observing true anomaly at different times :

t0=0,v=81.6
t1=3600s, v=103.5
t2=7200s, v=119.0
…

Can we find orbital parameters "a" and "e"?

This can be a term project

$$M = t\frac{360^o}{T}$$

$$M = E - eSin(E)$$

$$\cos(u) = \frac{\cos(E) - e}{1 - e\cos(E)}$$

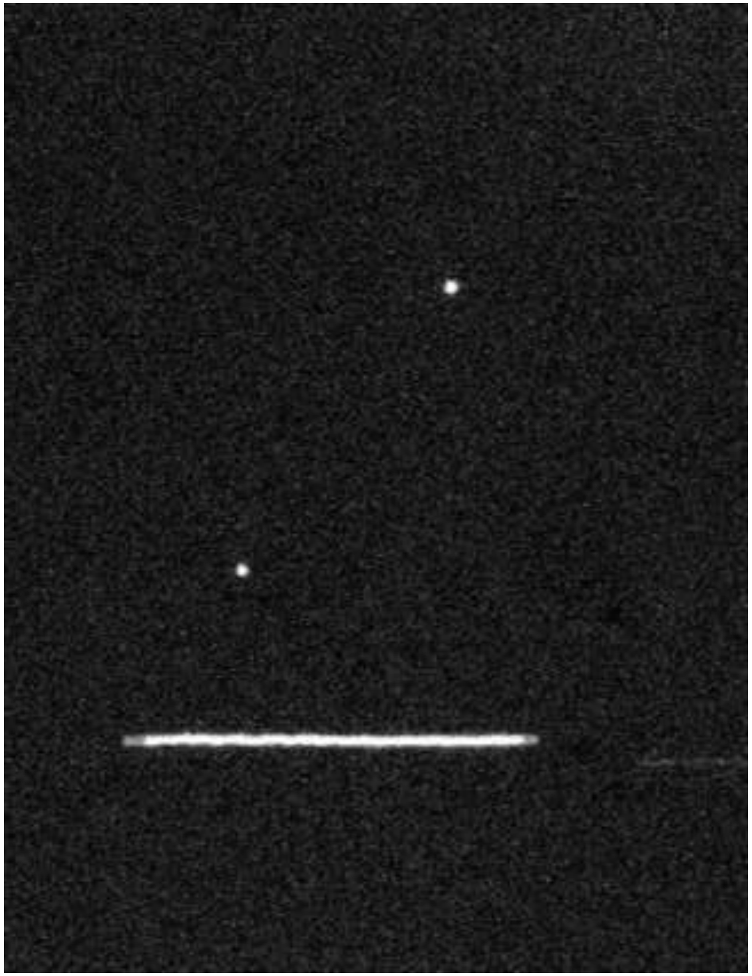
$$r = \frac{a(1 - e^2)}{1 + e\cos(v)}$$

Satellite Orbits
How to Calculate Orbits

Geostationary satellites angles are observed using telescopes and orbital parameters are calculated.

LEO satellite orbits are calculated using radar (angle and radial distance)

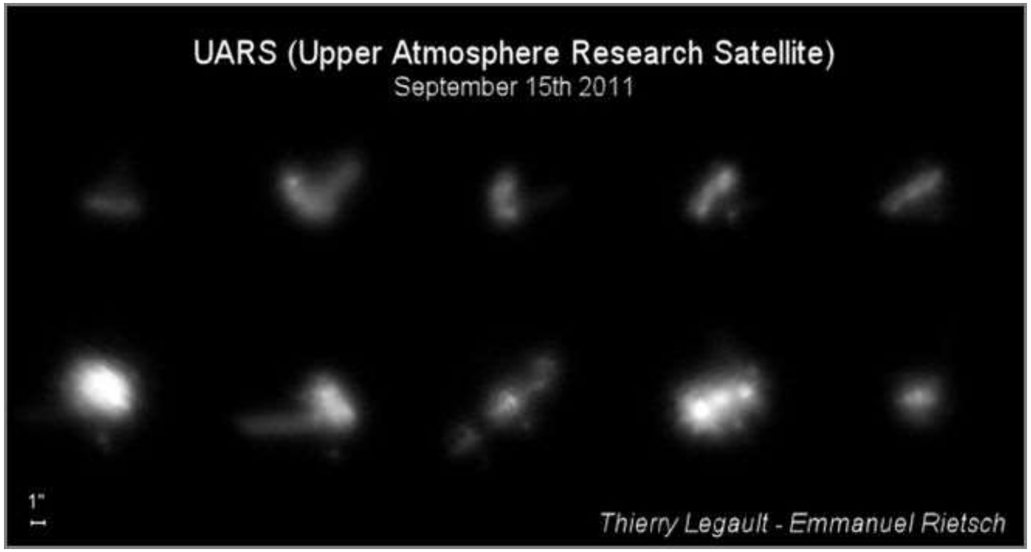
Satellite operator calculates orbits of their satellite by measuring radial distance (ranging) and azimuth, elevation angles.



Satellite Orbits
How to Calculate Orbits

LEO satellite orbits are calculated using radar (angle and radial distance)

Big space objects such as ISS's shape can be observed using telescopes.



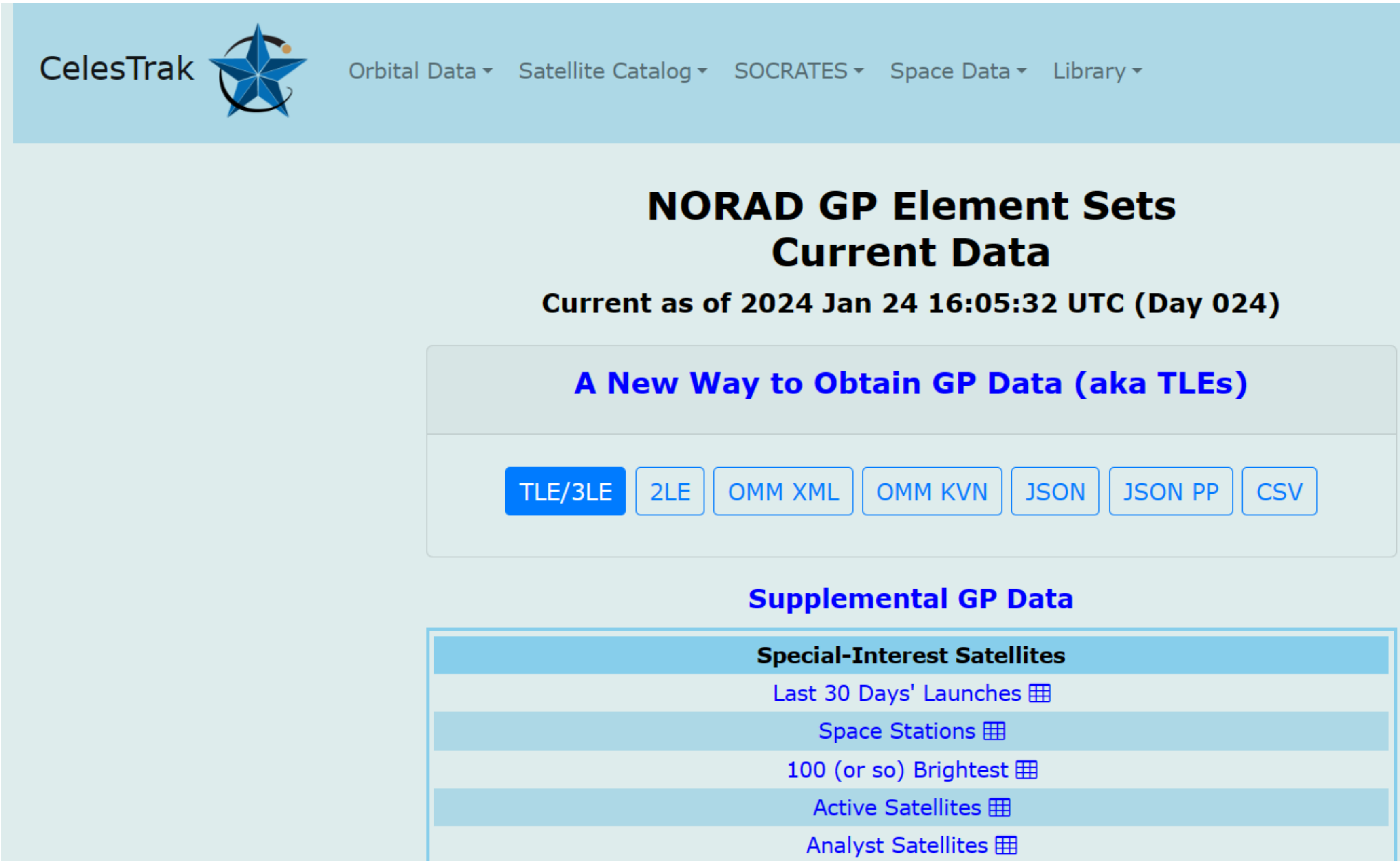
Satellite Orbits
Two Line Element Set

NORAD (North American Aerospace Command) maintains general perturbation element sets on all resident space objects. These element sets are periodically refined so as to maintain a reasonable prediction capability on all space objects.

These element sets are provided to users through www.celestrak.org , a web page maintained by Dr. T.S. Kelso

www.space-track.org is another page maintained by US Government Joint Functional Component Command for Space (JFCC SPACE) provides TLE to registered users

Satellite Orbits
Two Line Element Set



Satellite Orbits
TLE Format

```
GOKTURK 2
1 39030U 12073A   24078.18769642  .00000633  00000+0  10425-3 0  9998
2 39030  97.7667 303.0203 0001974  96.6734 263.4700 14.73703696603531
```

Line 1

Column	Description
01	Line Number of Element Data
03-07	Satellite Number
08	Classification (U=Unclassified)
10-11	International Designator (Last two digits of launch year)
12-14	International Designator (Launch number of the year)
15-17	International Designator (Piece of the launch)
19-20	Epoch Year (Last two digits of year)
21-32	Epoch (Day of the year and fractional portion of the day)
34-43	First Time Derivative of the Mean Motion
45-52	Second Time Derivative of Mean Motion (decimal point assumed)
54-61	BSTAR drag term (decimal point assumed)
63	Ephemeris type
65-68	Element number
69	Checksum (Modulo 10)

(Letters, blanks, periods, plus signs = 0; minus signs = 1)

Line 2

Column	Description
01	Line Number of Element Data
03-07	Satellite Number
09-16	**Inclination** [Degrees]
18-25	Right Ascension of the Ascending Node [Degrees]
27-33	**Eccentricity** (decimal point assumed)
35-42	Argument of Perigee [Degrees]
44-51	**Mean Anomaly** [Degrees]
53-63	**Mean Motion** [Revs per day]
64-68	Revolution number at epoch [Revs]

69 Checksum (Modulo 10)

Satellite Orbits
TLE of Gokturk-2

GOKTURK 2
1 39030U 12073A   17010.14461809 .00000060 00000-0 17178-4 0 9994
2 39030 **98.0117** 265.3320 **0000976** 139.5301 220.5980 **14.726148682**17292

Gokturk-2 important parameters:
Mean motion: 14.726148682 rev/day => T=86400/**14.726148682**/60=97.8 min/rev,

$$\boldsymbol{T = 2\pi\sqrt{\frac{a^3}{GM}}}$$ GM=398600,4418 km3/s2

$$\boldsymbol{a = \sqrt[3]{GM(T/2\pi)^2}}$$ =**7031km**

remember Earth Radius 6378km, means **653 km from Earth Surface**

Inclination: **98.0117** degree, polar orbit

Eccentricity: **0.0000976**, too small, almost circular orbit

Satellite Orbits
TLE of Turksat 3A

TURKSAT 3A
1 33056U 08030B 17009.08717543 .00000141 00000-0 00000+0 0 9995
2 33056 **0.0508** 169.8101 **0003713** 105.9037 266.4559 **1.00269619** 31529

Turksat-3A important parameters:
Mean motion: 1.00269619 rev/day => 86400/1.000269619= 86168 sec
$\boldsymbol{a = \sqrt[3]{GM(T/2\pi)^2}}$ = 42165 km

Inclination: 0.0508 degree, equatorial orbit
Eccentricity: 0.0003713 , too small, almost circular orbit

Satellite Orbits
TLE of Gokturk-2 and Turksat 3A

GOKTURK 2
1 39030U 12073A 17010.14461809 .00000060 00000-0 17178-4 0 9994
2 39030 98.0117 265.3320 **0000976** 139.5301 **220.5980** 14.72614868217292
TURKSAT 3A
1 33056U 08030B 17009.08717543 .00000141 00000-0 00000+0 0 9995
2 33056 0.0508 169.8101 **0003713** 105.9037 **266.4559** 1.00269619 31529

Gokturk-2:
Mean anomaly: 220.5980 calculated E=220.59806, true anomaly=220.59442 degree

Turksat-3A:
Mean anomaly: 266.4559 calculated E=266.456, true anomaly=266.435degree

(due to very small eccentricity three angles are close to each other)

Satellite Orbits
TLE and Orbit Prediction

GOKTURK 2
1 39030U 12073A **<u>17010.14461809</u>** .00000060 00000-0 17178-4 0 9994
2 39030 98.0117 265.3320 0000976 139.5301 220.5980 14.72614868217292
TURKSAT 3A
1 33056U 08030B **<u>17009.08717543</u>** .00000141 00000-0 00000+0 0 9995
2 33056 0.0508 169.8101 0003713 105.9037 266.4559 1.00269619 31529

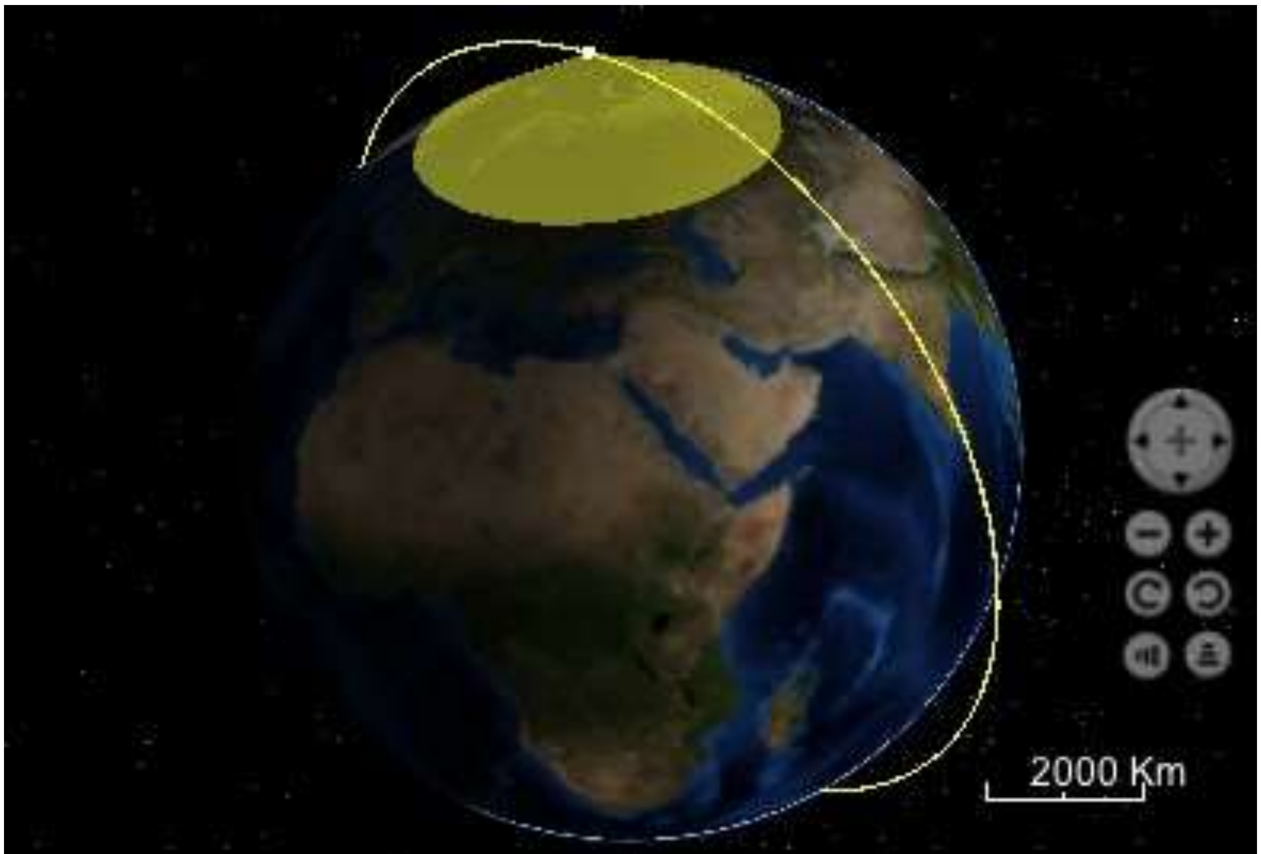
TLE provides a snapshot of the orbit at given **epoch date (e.g. 2017, 01 day, 0.14461809x24 hours).** There are orbit estimation algorithms to predict the orbit for a future date. **SGP4 (Simplified General Perturbations)** is well known.

Satellite Orbits
Orbit Simulation Software

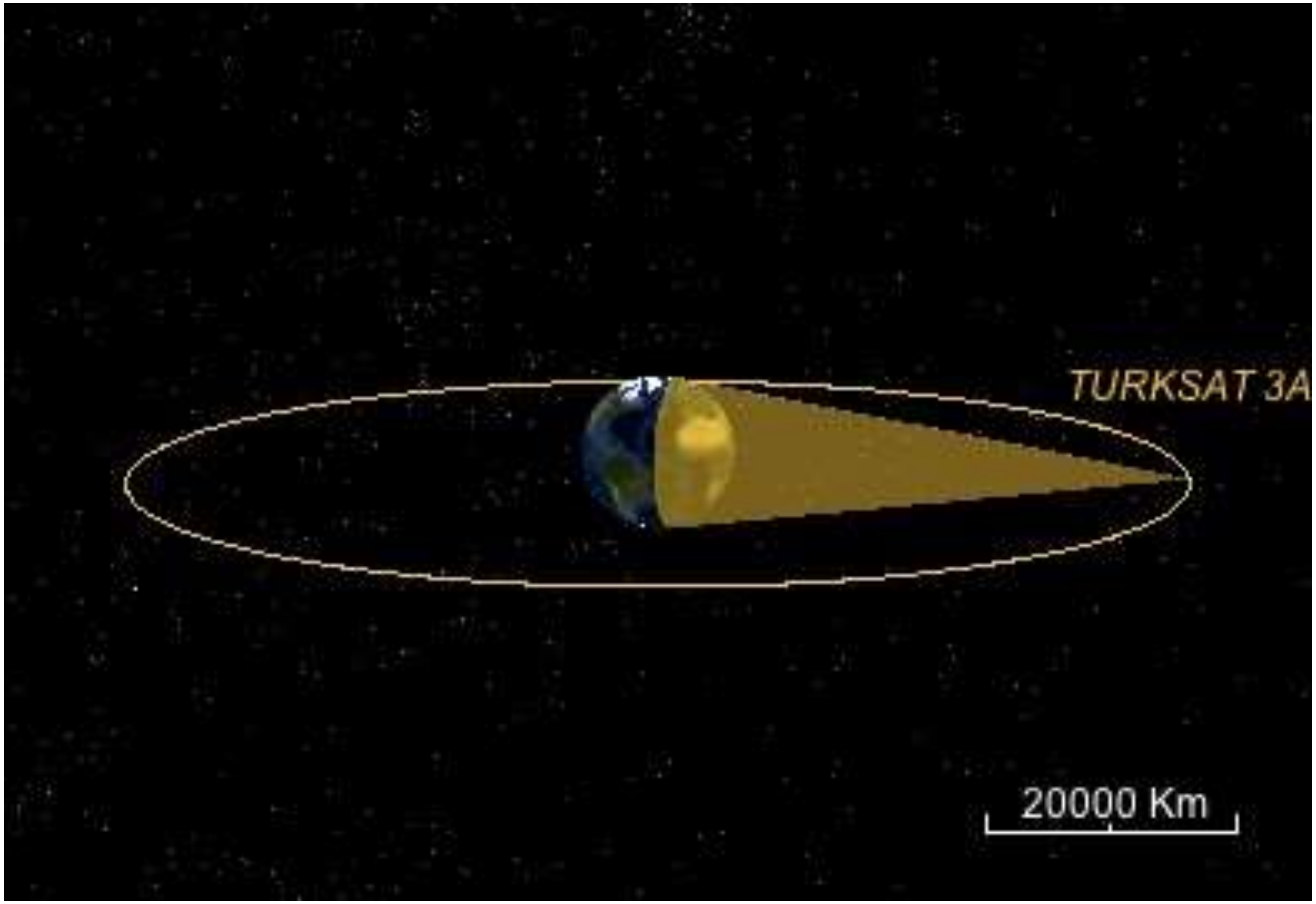
- MATLAB, Satellite Communication Toolbox

- JsatTrak free for windows and MacOS, SGP4 simulations. http://www.gano.name/shawn/JSatTrak/

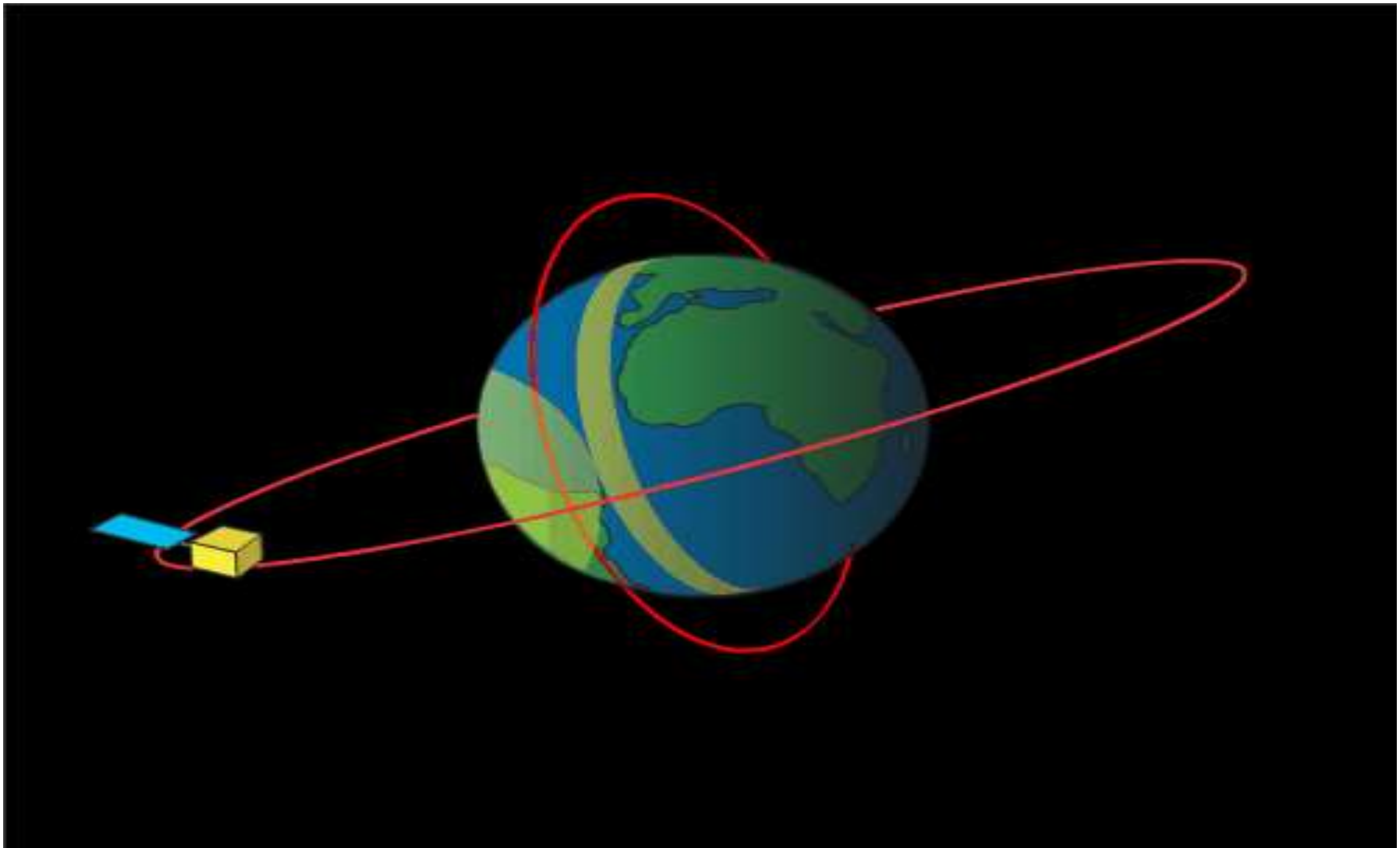
Satellite Orbits
Gokturk-2 Orbit View



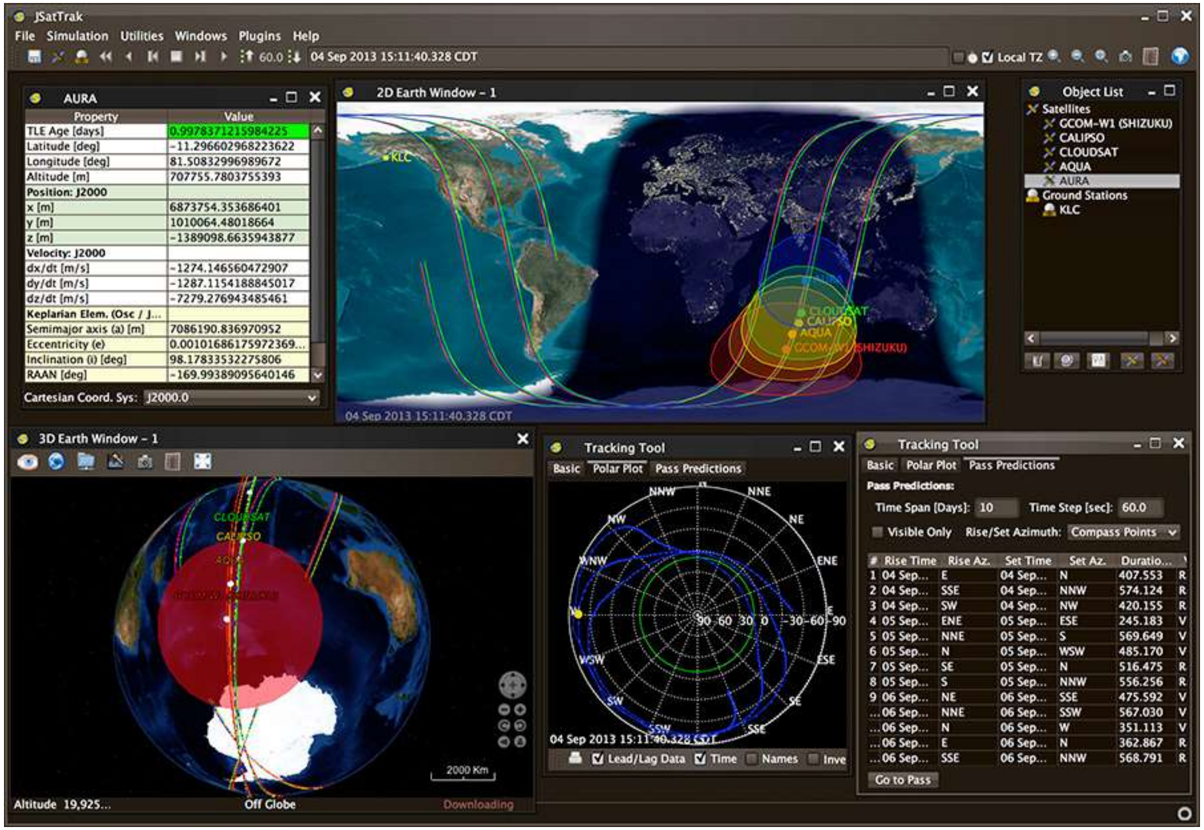
Satellite Orbits
Turksat-3A Orbit View



Satellite Orbits
GEO and LEO Orbit View



Satellite Orbits
JsatTrak



[JSatTrak - Java Satellite Tracker by Shawn Gano]

Satellite Track
LEO

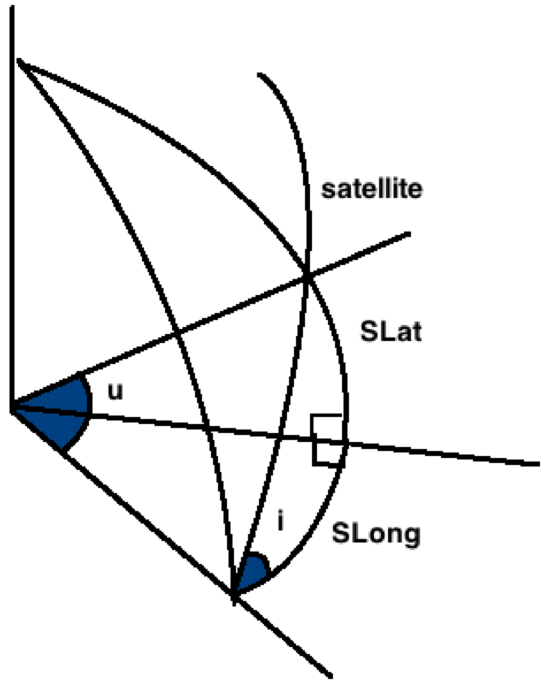
- We can assume that satellite sub-point is rotating on Earth Surface with satellite period.
- We need to subtract the Earth rotation from the satellite longitude to find true longitude

$$u = t\frac{2p}{T}, ELong = t\frac{2p}{T_E}$$

$$\sin(SLat) = \sin(i)\sin(u)$$

$$\tan(Slong) = \tan(u)\cos(i)$$

$$Long = Slong - ELong$$



Satellite Track
LEO

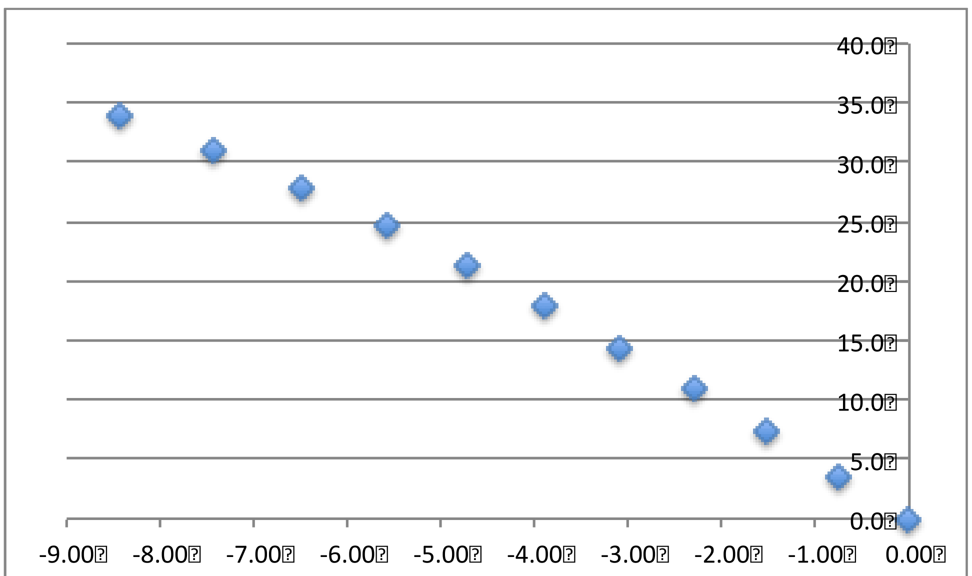
- Example: Gokturk-2, 600 seconds simulation T=98min.
- Satellite moves from South to North (daytime passing). Earth moves to East. Satellite moves to West due to 98 degree inclination. Total relative motion of the satellite is to West.

$$u = t\frac{2p}{T}, ELong = t\frac{2p}{T_E}$$

$$\sin(SLat) = \sin(i)\sin(u)$$

$$\tan(Slong) = \tan(u)\cos(i)$$

$$Long = Slong - ELong$$

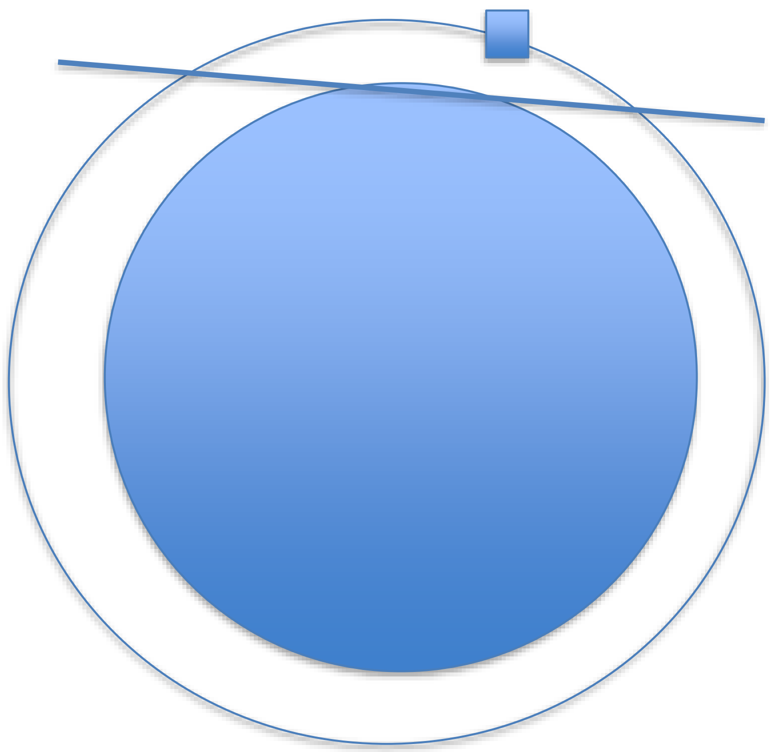


Satellite Track
LEO

- At each period of the satellite Earth will rotate and satellite longitude will shift to West for the same latitude

$$Slong = t\frac{360}{Ts}, Elong = t\frac{360}{Te}$$
$$Dlong = Slong - Elong$$
$$\mathrm{t} = Ts$$
$$Dlong = 360\left(1 - \frac{Ts}{Te}\right)$$
$$Dlong = 360\left(1 - \frac{1}{\mathrm{revday}}\right)$$
$$Dlong = -\frac{360}{revday}$$
$$\boldsymbol{Dlong = \frac{360}{14.726} = 24.44deg}$$

Satellite Track
LEO



Sun Synchronous Orbit

- satellite will always observe a point on the Earth as if constantly at the same time of the day, for example, passing the city of Paris every day at noon exactly.
- Satellite orbits will shift from SSO by years if there is no orbit control

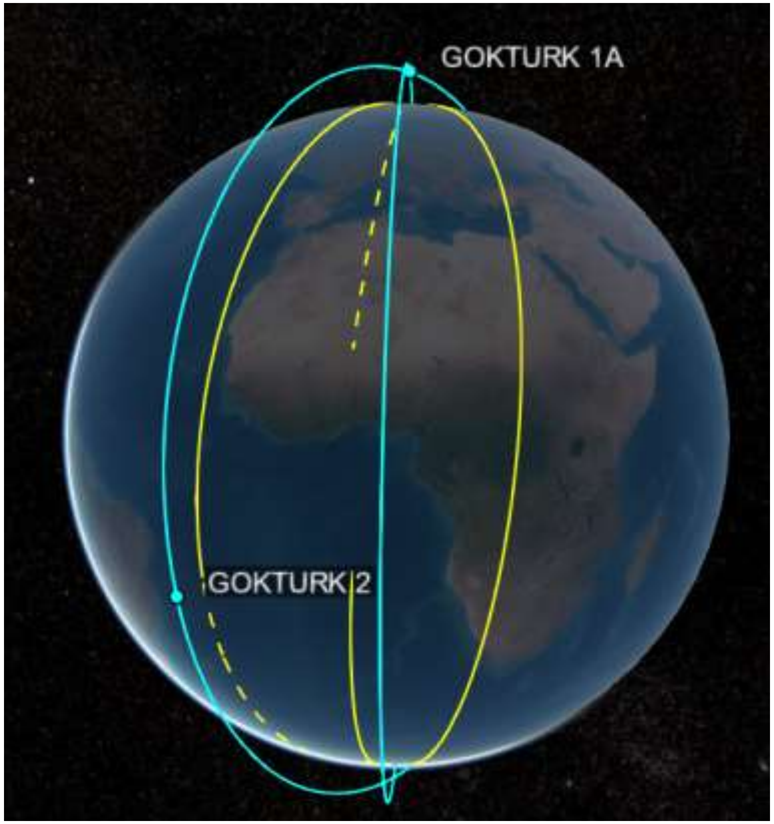
Satellite Toolbox

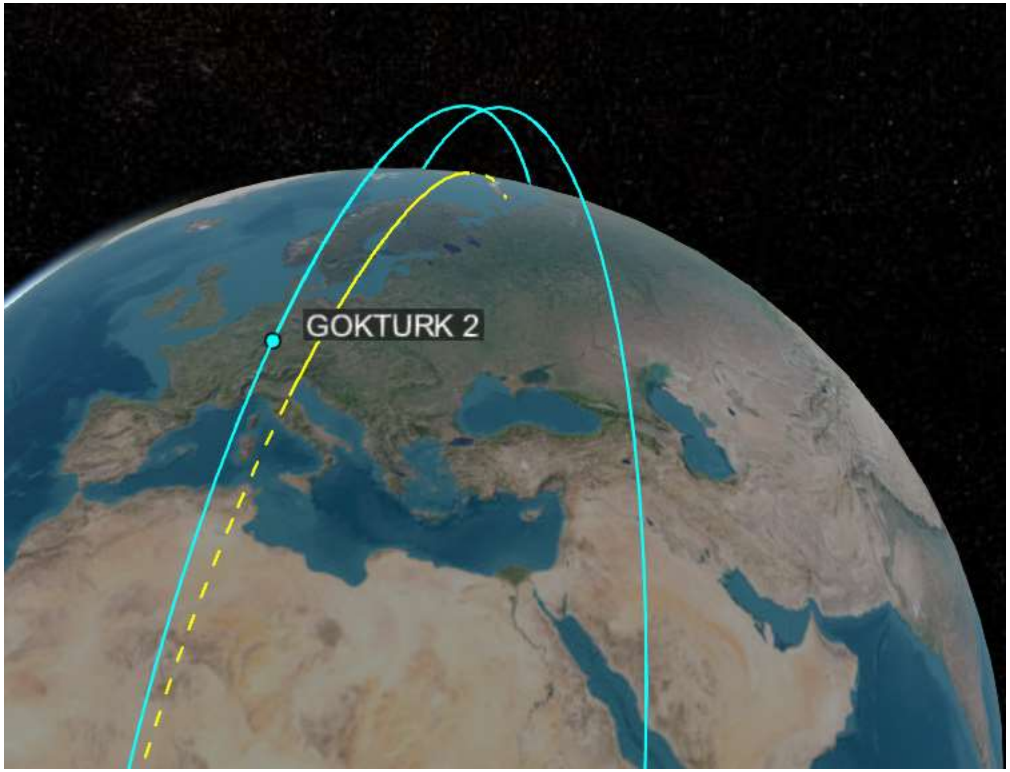
```
GOKTURK 1A
1 41875U 16073A   24024.08507703  .00000952  00000+0  19553-3 0  9995
2 41875  98.1169 280.1581 0001346  85.2175 274.9181 14.62838124380897
GOKTURK 2
1 39030U 12073A   24024.13954624  .00001030  00000+0  16540-3 0  9996
2 39030  97.7730 251.2375 0000929  66.9582 293.1725 14.73603413595573
TURKSAT 3A
1 33056U 08030B   24024.05004469  .00000147  00000+0  00000+0 0  9998
2 33056   0.0165 129.1496 0003238 185.3196 228.3855  1.00274063 57303
```

```
startTime = datetime(2024,1,24,19,38,0);
stopTime = startTime + hours(48);
sampleTime = 60;
sc = satelliteScenario(startTime,stopTime,sampleTime);
sat = satellite(sc,"gokturk.tle");
show(sat)
groundTrack(sat,"LeadTime",1200);
```

Satellite Toolbox

GOKTURK 1A
1 41875U 16073A   24024.08507703 .00000952 00000+0 19553-3 0 9995
2 41875 **98.1169** 280.1581 0001346 85.2175 274.9181 **14.62838124**380897
GOKTURK 2
1 39030U 12073A   24024.13954624 .00001030 00000+0 16540-3 0 9996
2 39030 **97.7730** 251.2375 0000929 66.9582 293.1725 **14.73603413**595573





Satellite Toolbox

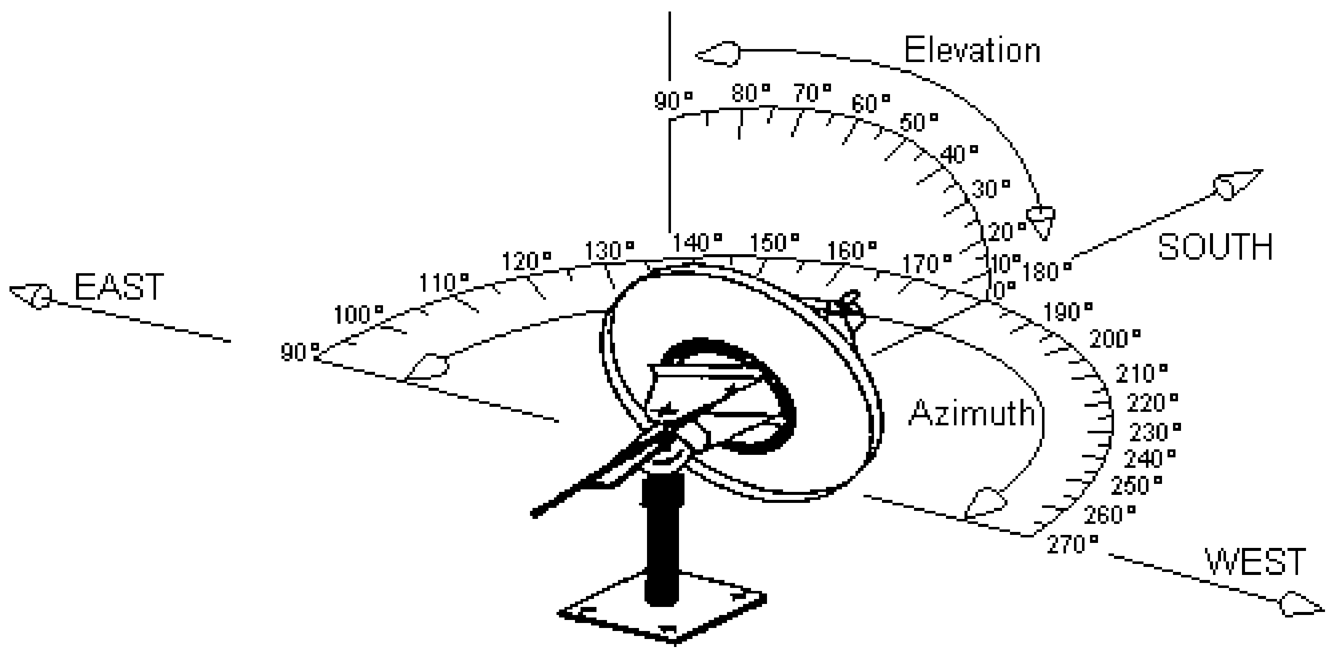
GOKTURK 1A
1 41875U 16073A   24024.08507703 .00000952 00000+0 19553-3 0 9995
2 41875 98.1169 280.1581 0001346 85.2175 274.9181 14.62838124380897
GOKTURK 2
1 39030U 12073A   24024.13954624 .00001030 00000+0 16540-3 0 9996
2 39030 97.7730 251.2375 0000929 66.9582 293.1725 14.73603413595573
TURKSAT 3A
1 33056U 08030B   24024.05004469 .00000147 00000+0 00000+0 0 9998
2 33056   0.0165 129.1496 0003238 185.3196 228.3855 1.00274063 57303

Satellite Toolbox

```
>> ele1 = orbitalElements(sat(1))

ele1 =

  struct with fields:

                 MeanMotion: 0.0610
               Eccentricity: 1.3460e-04
                Inclination: 98.1169
RightAscensionOfAscendingNode: 280.1581
         ArgumentOfPeriapsis: 85.2175
                 MeanAnomaly: 274.9181
                     Period: 5.9063e+03
                      Epoch: 24-Jan-2024 02:02:30
                      BStar: 1.9553e-04
```

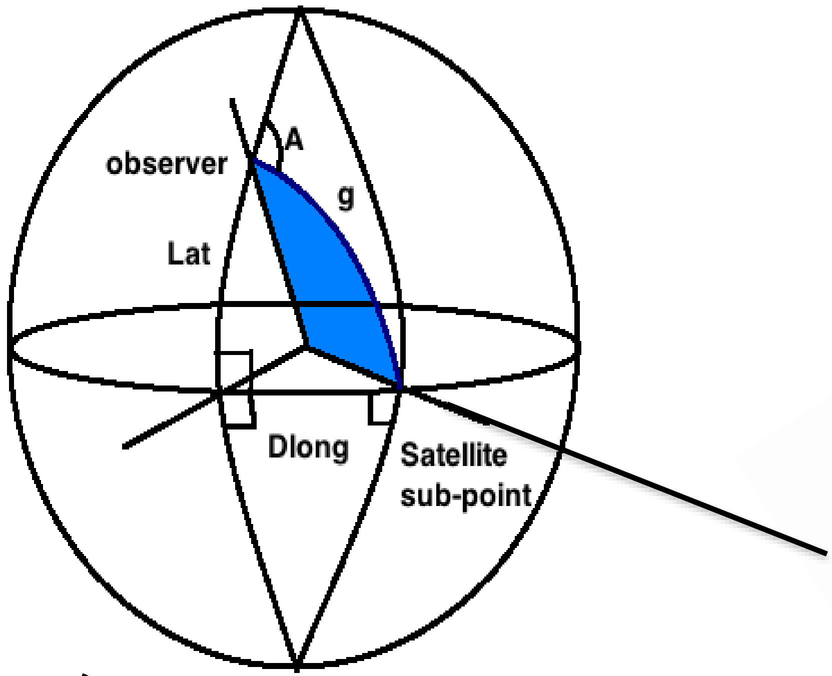
Satellite Looking Angles

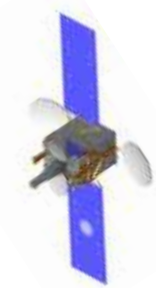
- Dish antennas are used for satellite communication. Antenna has to point to the satellite.
- Azimuth : Angle from the North
- Elevation: Tilt angle from the ground plane



Satellite Looking Angles
Azimuth

- Great circle(g), center of Earth, observer and satellite plane
- **Great circle angle** is calculated first using cosine rule in spherical trigonometry
- Azimuth is calculated using sine rule in spherical trigonometry





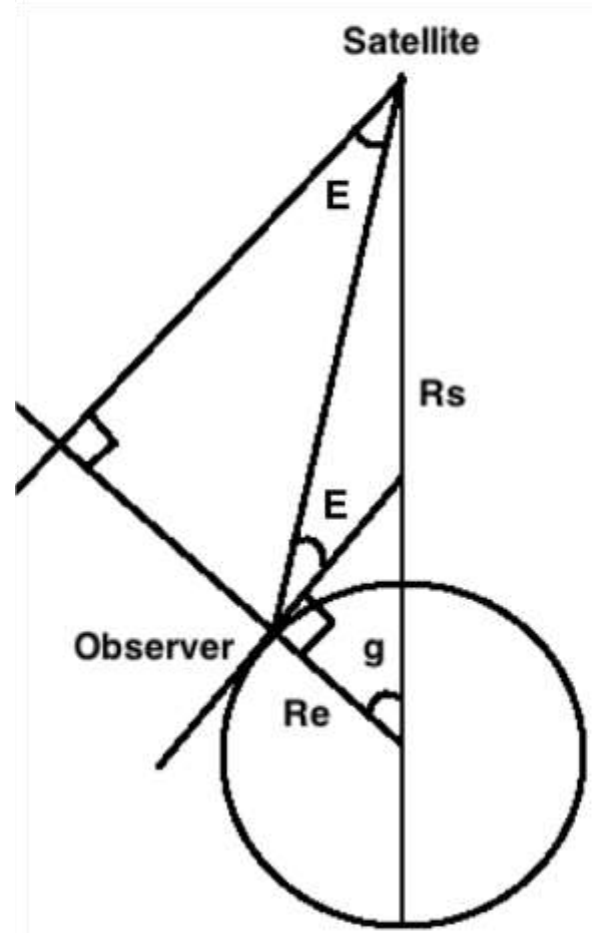
$$\Delta long = long_{sat} - long_g$$

$$\cos(g) = \cos(\Delta long) \times \cos\left(lat_g\right)$$

$$Azimuth = 180 - Asin\left(\frac{\sin(\Delta long)}{\sin(g)}\right)$$

Satellite Looking Angles
Elevation

- Consider three point plane: Center of the Earth, observer, satellite.
- Elevation angle "E" is measured wrt to tangent to observer location



$$E = Atan\left(\frac{Rs.\cos(g) - Re}{Rs.\sin(g)}\right)$$

Satellite Looking Angles Example

- Calculate azimuth and elevation at Ankara (33E, 40N) for Turksat-3A at 42 degree East.

$$\mathrm{g} = \mathrm{Acos}\{\, \cos\left(long_{sat} - long_g\right) \cos\left(lat_g\right) \,\}$$

$$\mathrm{g} = \cos(42 - 33)\cos(40) = 40.8\ \mathrm{deg}$$

$$\mathrm{E} = Atan\left(\frac{Rs.\cos(g) - Re}{Rs.\sin(g)}\right)$$

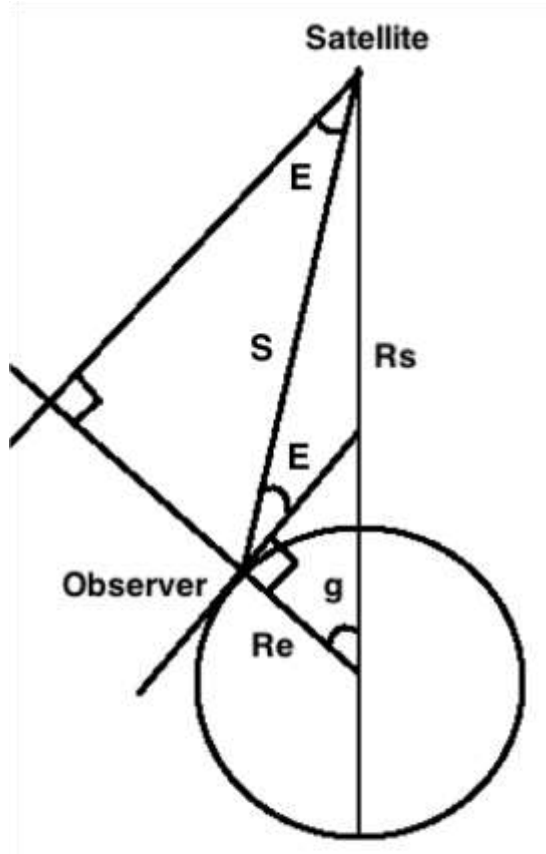
$$E = 42.8\ deg$$

$$A = 180 - Asin\left(\frac{\sin\left(long_{sat} - long_g\right)}{\sin(g)}\right)$$

$$A = 166.2\ deg$$

Satellite Slant Range

- Slant range is distance to satellite from the observer.
- This distance will be important to calculate the signal loss from/to the satellite.



$$S = \sqrt{R_S^2 + R_e^2 - 2 R_S R_e \cos(g)}$$

$$\cos(g) = \cos(DLong)\cos(Lat_{Observer})$$

Satellite Slant Range Turksat-3A Example

- Slant range is distance to satellite from the observer.
- This distance will be important to calculate the signal loss from/to the satellite.

$$\cos(g) = \cos(\Delta Long)\cos(Lat_{Observer})$$

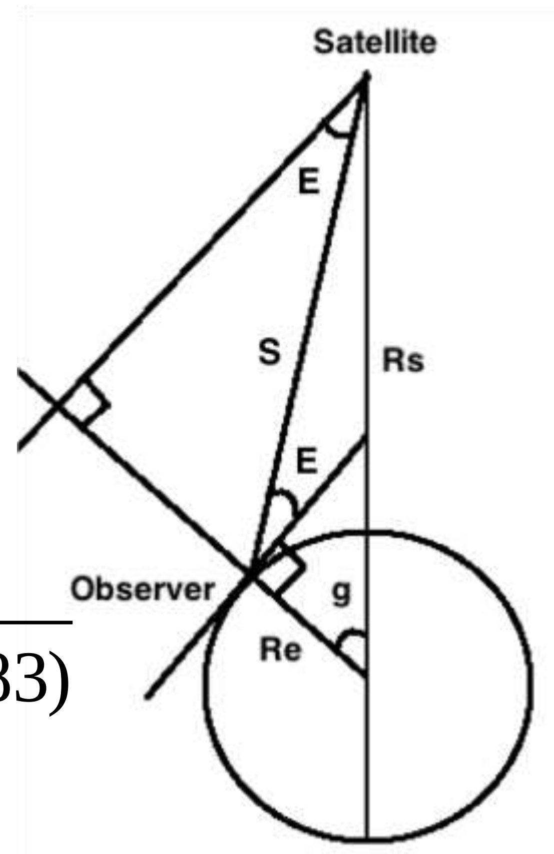
$$\cos(g) = \cos(42 - 33)\cos(40)$$

$$g = 40.83^{o}$$

$$S = \sqrt{R_S^2 + R_e^2 - 2R_S R_e \cos(g)}$$

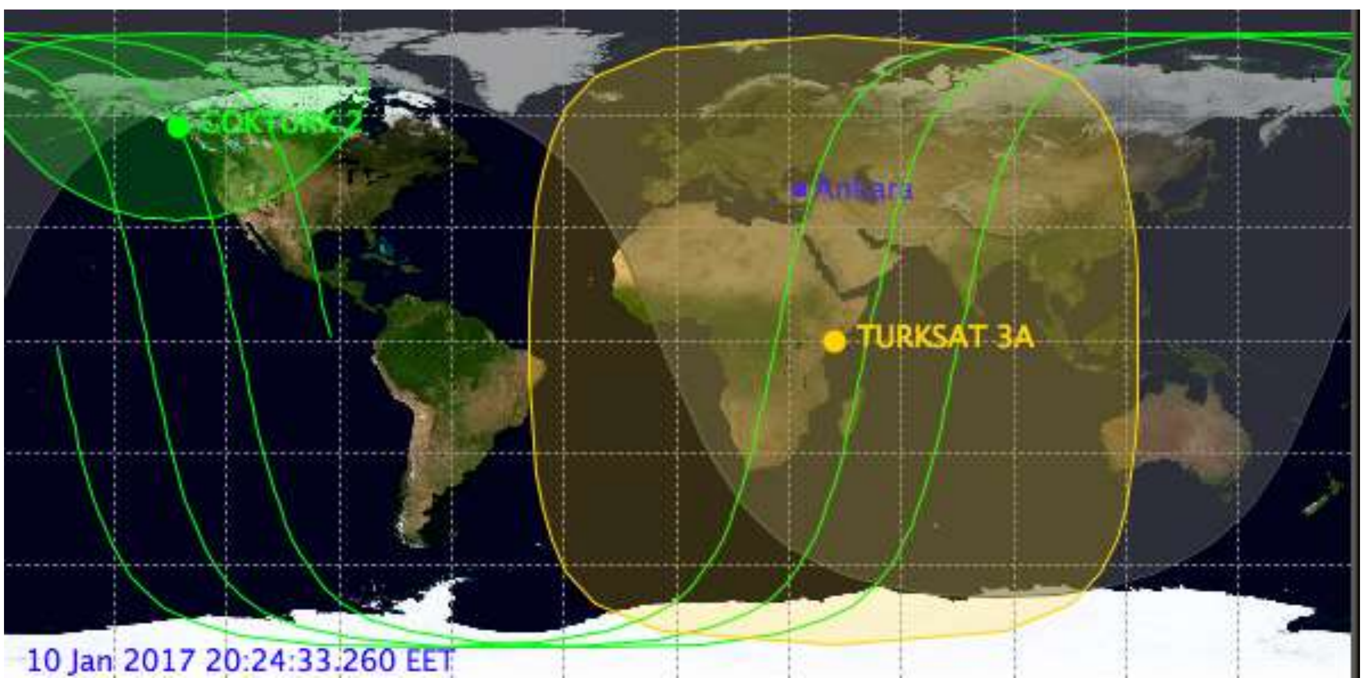
$$S = \sqrt{42164^2 + 6378^2 - 2.42164.6378\cos(40.83)}$$

$$S = 37570km$$



Satellite Track

- Geostationary satellites have a fixed sub-satellite point on equator circle. Thus their position is given by the longitude only.
- LEO satellites will have varying sub-satellite point on the Earth



Satellite Track
GEO

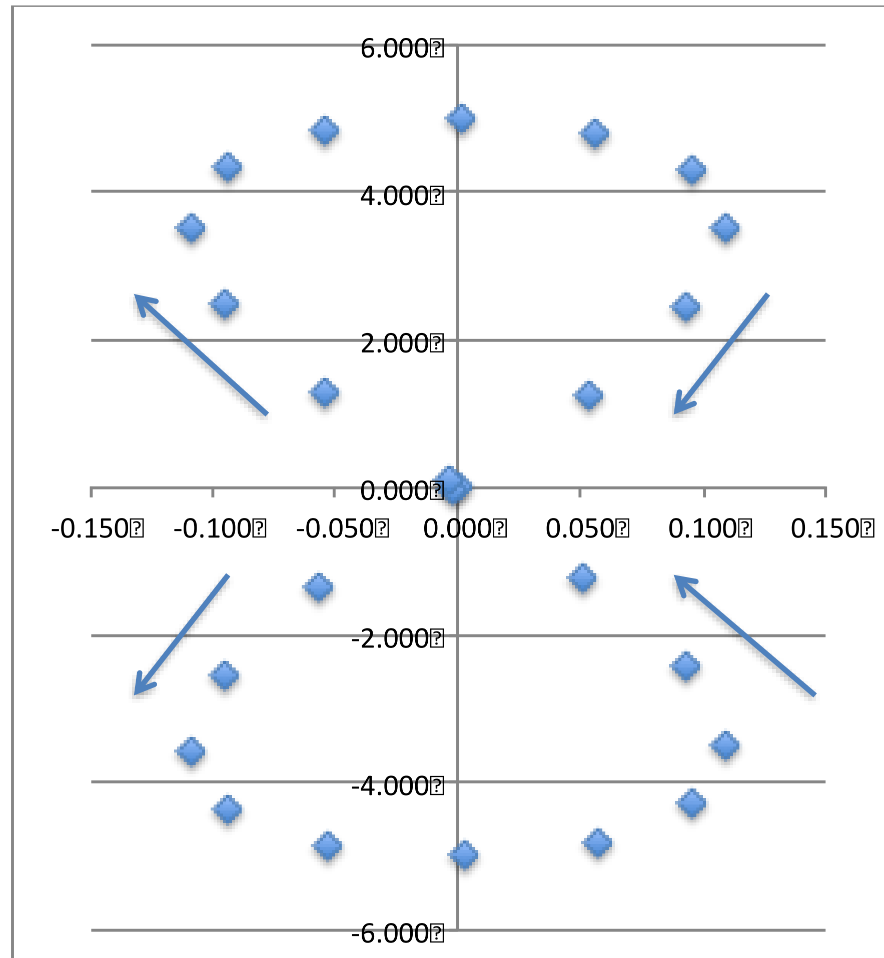
- GEO satellites with inclination will draw shape "8" excluding longitude drift.
- Example i=5 degree, 24 hour calculation

$$u = t\frac{2p}{T}, ELong = t\frac{2p}{T_E}$$

$$\sin(SLat) = \sin(i)\sin(u)$$

$$\tan(Slong) = \tan(u)\cos(i)$$

$$Long = Slong - ELong$$

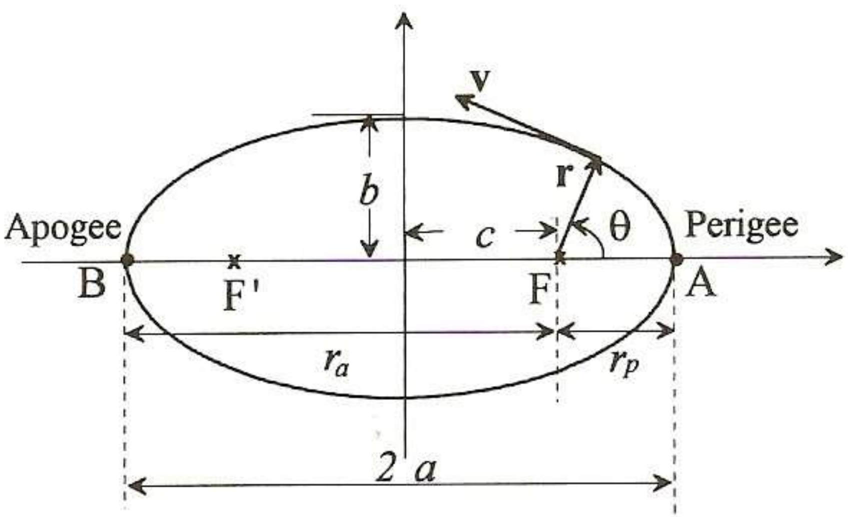


Communication Satellites
Delta-V

- Velocity of a circular orbit is constant
- Velocity at perigee is higher than apogee

$$V = \sqrt{\frac{GM}{R}}\ (circular)$$

$$V = \sqrt{GM\left(\frac{2}{R} - \frac{1}{a}\right)}\ (elliptical)$$

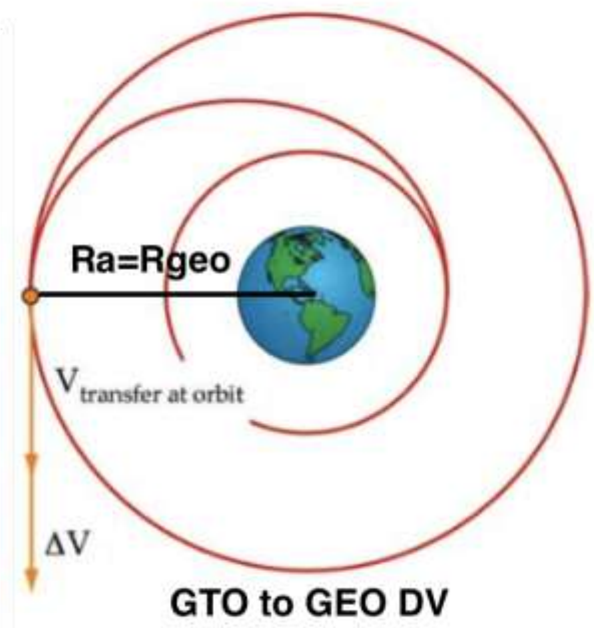


Communication Satellites
Delta-V

- Launcher leaves the satellite at GTO eliptical orbit
- Change of orbit requires change of DV
- If we perform a DV maneuver at apogee of GTO orbit, we circularize the orbit to GEO with Rgeo=42164km, Ra=42164km

$$V_a = \sqrt{GM\left(\frac{2}{R_a} - \frac{1}{a}\right)}, V + DV = \sqrt{\frac{GM}{R_{GEO}}}$$

$$DV = \sqrt{\frac{GM}{R_{GEO}}} - \sqrt{GM\left(\frac{2}{R_a} - \frac{1}{a}\right)}$$



Communication Satellites Delta-V

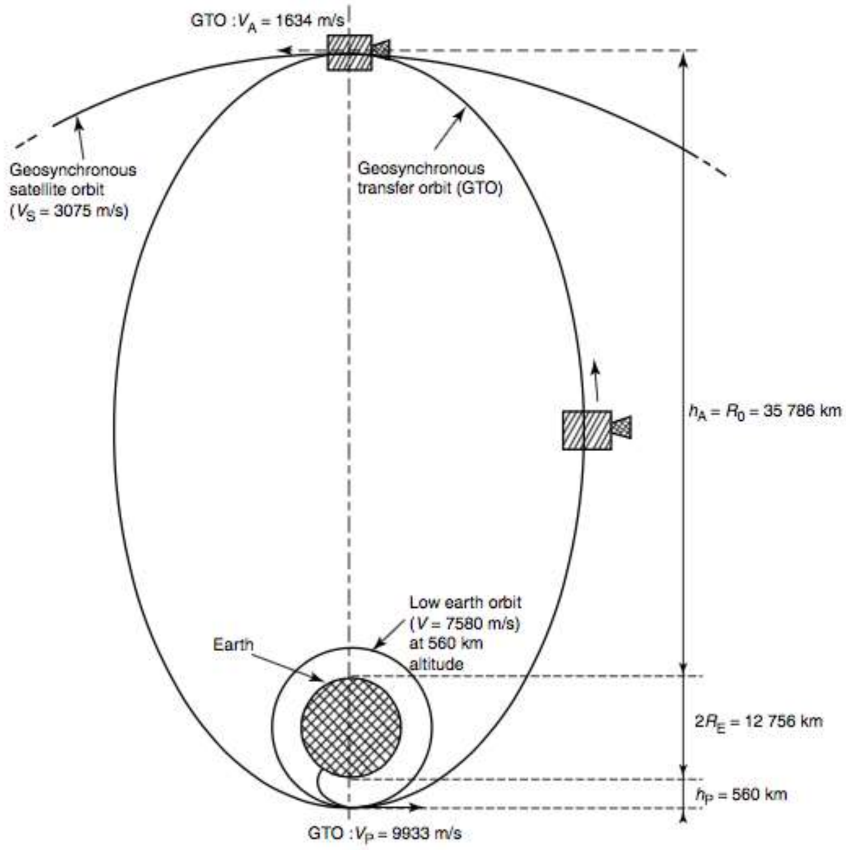
- Going from an GTO elliptical orbit to GEO circular orbit: Rocket leaves the satellite at GTO orbit with Rp=6938km, Ra=42164km (a=24551). What is the required DV for GEO.

$$V = \sqrt{GM\left(\frac{2}{R} - \frac{1}{a}\right)}$$

$$V_a = \sqrt{GM\left(\frac{2}{42164} - \frac{1}{24551}\right)} = 1634 m/s$$

$$V_{GEO} = \sqrt{\frac{GM}{42164}} = 3074 m/S$$

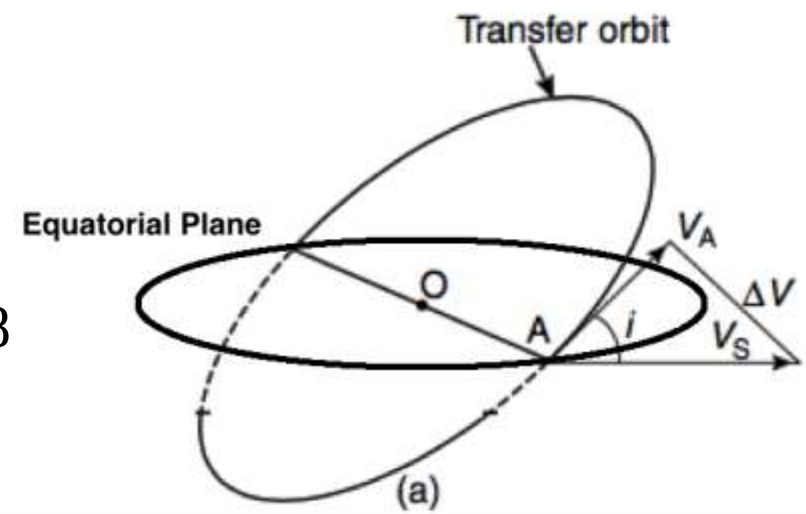
$$DV = 3074 - 1634 = 1440 m/s$$



Communication Satellites
Delta-V for GTO to GEO

- Inclination change together with circularization of the orbit can be performed. GTO to GEO inclination correction and circularization maneuver performed at apogee of GTO orbit due to lower velocity at apogee

	1st Evaluation
Apogee altitude (km)	35920
Perigee altitude (km)	249.2
Inclination (°)	6.00



$$V = \sqrt{GM\left(\frac{2}{R} - \frac{1}{a}\right)},\ a = \frac{35920 + 249.2}{2} + 6378$$

$$V_A = \sqrt{GM\left(\frac{2}{42298} - \frac{1}{24462.6}\right)} = 1597 m/s$$

$$V_{GEO} = 3074 m/S$$

$$DV = \sqrt{3074^2 + 1597^2 - 2.3074.1597.\cos(6^o)} = 1494 m/s$$

Communication Satellites Rocket Equation

- Propellant defines the lifetime of the satellite. Satellite can not keep the orbital position without propellant due to perturbations.

$$\Delta \boldsymbol{M} = \boldsymbol{M}\left(\mathbf{1} - \boldsymbol{e}^{-\frac{-\Delta \boldsymbol{V}}{\boldsymbol{go.Isp.eff}}} \right)$$

M: satellite mass before maneuver
Isp: Specific impulse of thruster
eff: efficiency of thruster
go: gravitational constant 9.80665 m/s2

Communication Satellites
Rocket Equation

- Satellites spend most of their fuel during orbit raising phase. They utilize 400N apogee motor after separation from rocket to go to GEO orbit.
- A 3000kg satellite needs 1494 m/s delta V for orbit raising. How much fuel required ? Isp=321 sec, efficiency=0.99. Satellite initial propellant is 1700 kg.

$$\Delta M = M(1 - e^{-\Delta V/(g0.Isp.eff)})$$

$$\Delta M = 3000.(1 - e^{-1494/(9.80665x321x0.99)})$$

$$\Delta M = 1142.5kg$$

%67 of the total propellant spent at orbit raising!

Communication Satellites Platform-Propellant Budget

Propellant Budget Calculation of Geostationary Satellites

[1]Şenol Gülgönül and *[1,2,3,4,] Nedim Sözbir

[1]BMC Power Engineering Department, İstanbul, Turkey
*[2]Faculty of Engineering, Department of Mechanical Engineering Sakarya University, Turkey
[3]Türksat A.Ş. Gölbaşı, Ankara, Turkey
[4]Tübitak MAM Gebze, Kocaeli, Turkey

Communication Satellites Propellant Budget

Velocity change required for orbit raising depends on the launcher selection. Launcher leaves the satellite at Geostationary Transfer Orbit (GTO) and satellite performs several apogee maneuvers (typically three) to go Geostationary Orbit (GEO). Space X Falcon-9 and Ariane-5 launcher's GTO orbit parameters are presented at Table.1 [10,11].

Table 1. Launcher Performances

Launcher	Inclination (degree)	Perigee (km)	Apogee (km)
Falcon-9	28.5	185	35,786
Ariane-5	6	250	35,943

Communication Satellites Propellant Budget

$$V = \sqrt{GM\left(\frac{2}{R} - \frac{1}{a}\right)}$$

where

GM : Earth Gravitational Constant, 398600.4418 km^3/s^2

R : Distance of the satellite to the center of the Earth, km

a : Semi-major axis of the satellite orbit, km

Semi-major of the GEO orbit is 42164km and the velocity at GEO orbit can be calculated using (2)

$$V_s = \sqrt{\frac{GM}{42164}} = 3074.7 \text{ m/s} \qquad (3)$$

Communication Satellites Propellant Budget

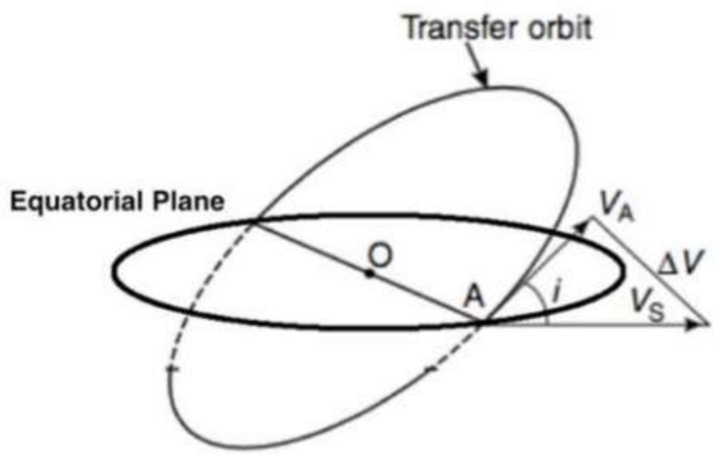


Figure 1. GTO to GEO orbit maneuver

The radius of the Earth can be assumed as 6378 km. For example, semi-major axis of the GTO orbit for Ariane-5 can be calculated by using altitude of apogee and perigee.

$$a = \frac{250 + 35943}{2} + 6378 = 24474.5 \text{ km} \tag{4}$$

Apogee velocity of the satellite is calculated using (2).

Communication Satellites Propellant Budget

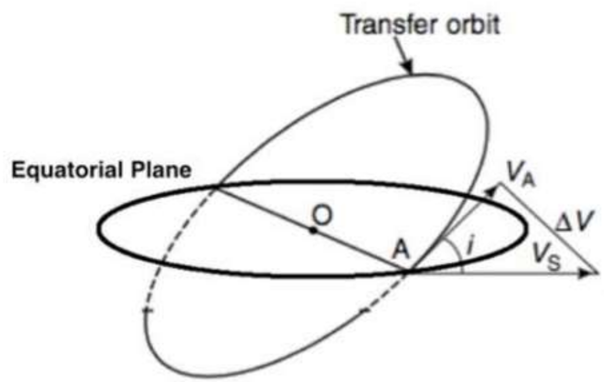


Figure 1. GTO to GEO orbit maneuver

$$V_A = \sqrt{GM\left(\frac{2}{35943+6378} - \frac{1}{244745}\right)} = 1597.1 \text{ m/s}$$

Finally, the required ΔV increment for Ariane-5 can be calculated using cosine rule.

$$\Delta V = \sqrt{V^2{}_a + V_S^2 - 2V_a V_S \cos(i)} = 1495.7 \text{ m/s}$$

Communication Satellites Propellant Budget

Velocity increment for East-West maneuvers depends on longitude of the satellite. Due to gravity distribution of the Earth 75 East and 105 West are stable orbital locations for geostationary satellite (see Fig. 2). Longitude acceleration for 42 degree East is given as 0.00171 deg/day^2. Yearly required ΔV_{EW} to correct this drift to is given [12].

$$\Delta V_{EW} = 3074.7\frac{0.00171x365}{3x361} = 1.77 \quad \text{m/s} \tag{7}$$

Acceleration versus spacecraft longitude

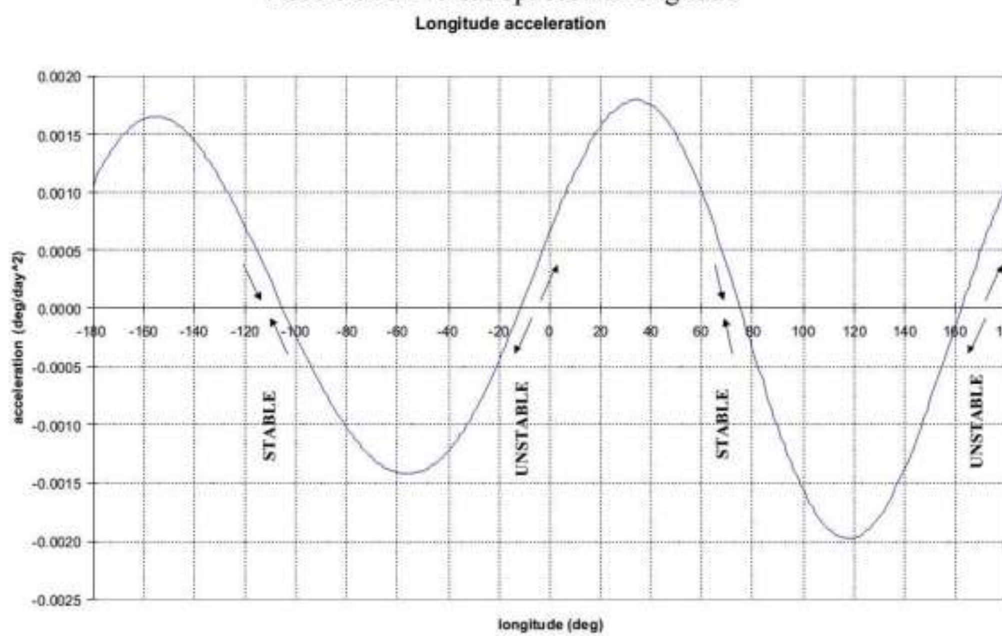


Figure 2. Longitude acceleration

Communication Satellites Propellant Budget

Natural evolution of yearly inclination changes between 0.75 and 0.95 degree (see Fig. 3). Average value of 0.85 deg/year can be used for calculations. North-South maneuvers are performed to correct the inclination of the satellite. Yearly required ΔV_{NS} to correct inclination is given as

$$\Delta V_{NS} = 3074.7 x i = 45.61 \text{ m/s} \tag{8}$$

where "i" is the inclination in radians [11].

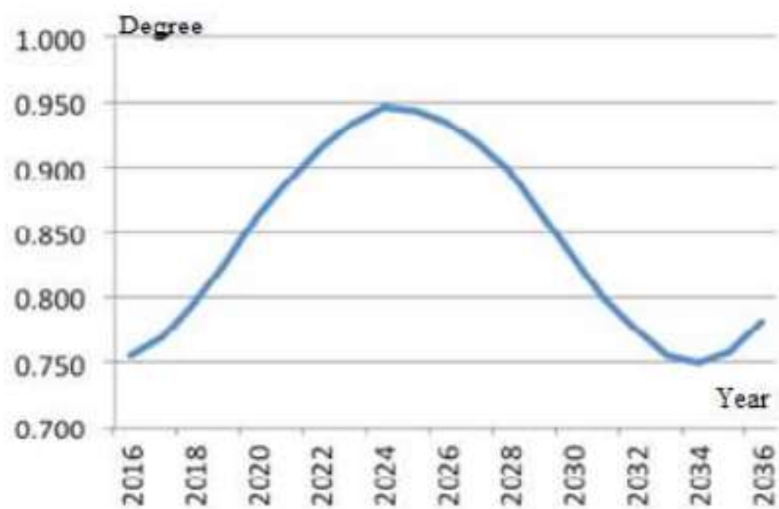


Figure 3. Yearly inclination change

Communication Satellites Propellant Budget

ITU radio regulation requires deorbit of the geostationary satellite to an orbit with a perigee no less than 200 km above the geostationary altitude [13]. Calculation of perigee altitude ΔH (km) is given in the ITU-R Recommendation

$$\Delta H > 235 + 1000.C_r.\frac{A}{M} \tag{9}$$

where

Cr is the reflectivity coefficient varying between 1 and 2,

A is the area (m^2),

M (kg) is the dry mass of the satellite.

The minimum perigee altitude can be calculated as 273 km for a typical geostationary satellite with 50 m^2 solar panel area and 1500 kg dry mass. 350 km is a practical value used by satellite operators including margins.

Communication Satellites Propellant Budget

ΔV for graveyard orbit is calculated using (1) with the assumption of Hohmann transfer to graveyard orbit. ITU recommends multiple maneuver strategy for orbit raising. First maneuver is performed to go from GEO orbit to a graveyard transfer orbit with apogee 42514 km, perigee 42164 km and semi-major axis 42339 km. Second maneuver is performed to circularize graveyard orbit with 42514 km radius.

$$
\begin{aligned}
\Delta V_1 &= \sqrt{GM\left(\frac{2}{42164}-\frac{1}{42339}\right)}-V_S \\
\Delta V_2 &= \sqrt{\frac{GM}{42514}}-\sqrt{GM\left(\frac{2}{42514}-\frac{1}{42339}\right)} \qquad (10) \\
\Delta V_{deo} &= \Delta V_1+\Delta V_2 = 12.7 \text{ m/s}
\end{aligned}
$$

There will be dispersions caused by launcher orbit injection accuracy, apogee maneuver firing (AMF) and on-orbit maneuvers. Thruster pointing errors, North-South maneuvers cross-coupling effects, attitude control (wheel unloading) will require additional delta-V to correct dispersions. Dispersions are based on experience of the satellite manufacturer and can be assumed 2% of the total delta-V for propellant budget calculations.

Communication Satellites Propellant Budget

Table 2. Propellant Budget Example-1

Lifetime	15	years			
Maneuver	DeltaV (m/s)	Isp (sec)	Efficiency	Delta M (kg)	Mass (kg)
					4000.0
AMF	1495.7	320	0.99	1528.4	2471.6
N/S	684.15	292	0.91	570.7	1900.9
E/W	26.55	292	0.91	19.3	1881.6
Deorbit	12.7	292	0.91	9.1	1872.5
Dispersions	44.4	292	0.91	31.6	1840.8
Propellant Mass				2159.2	
Dry Mass				1840.8	

Communication Satellites Propellant Budget

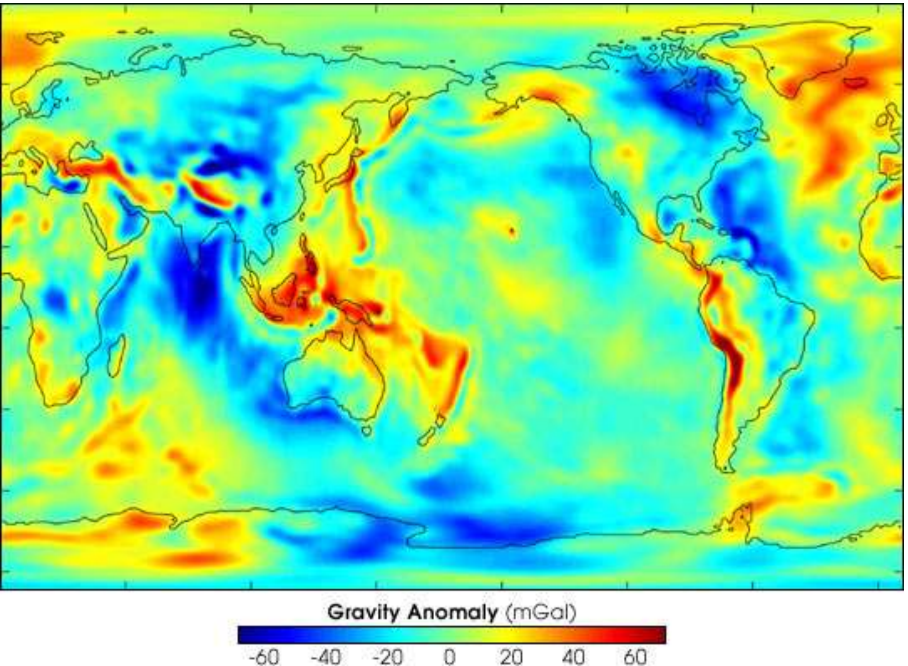
Table 3. Propellant Budget Example-2

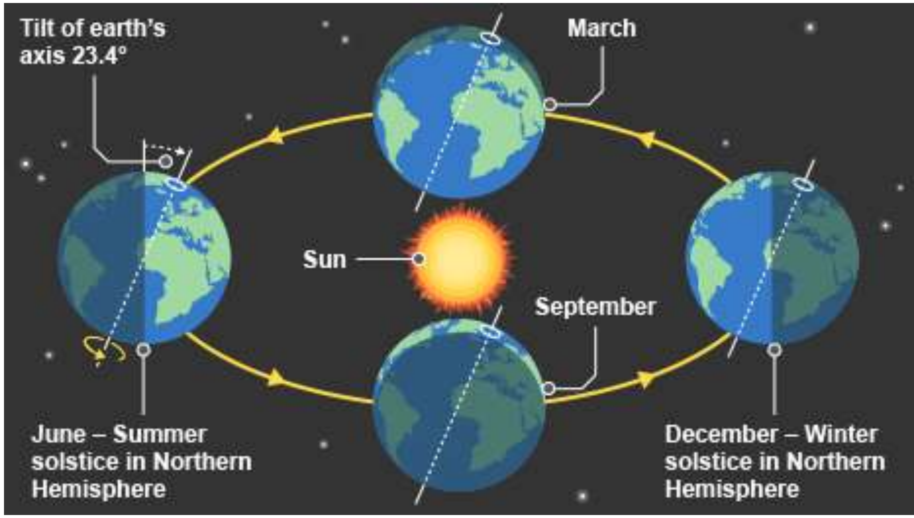
Lifetime	15	years			
Maneuver	DeltaV (m/s)	Isp (sec)	Efficiency	Delta M (kg)	Mass (kg)
					2716.1
AMF	1495.7	320	0.99	1037.8	1678.3
N/S	684.15	292	0.91	387.5	1290.7
E/W	26.55	292	0.91	13.1	1277.7
Deorbit	12.7	292	0.91	6.2	1271.4
Dispersions	44.4	292	0.91	21.5	1250.0
Propellant Mass				1466.1	
Dry Mass				1250.0	

Communication Satellites
Orbit Perturbations

There are three main perturbation force for GEO orbits:

1. Non-Spherical Earth : Due to gravity distribution of Earth 75 East and 105.3 West are stable points for GEO satellites. Causes to drift
2. Sun and Moon gravitational forces: 23.4 degree between equatorial and ecliptic planes. Increases the inclination of the orbit
3. Solar Pressure: increase the eccentricity

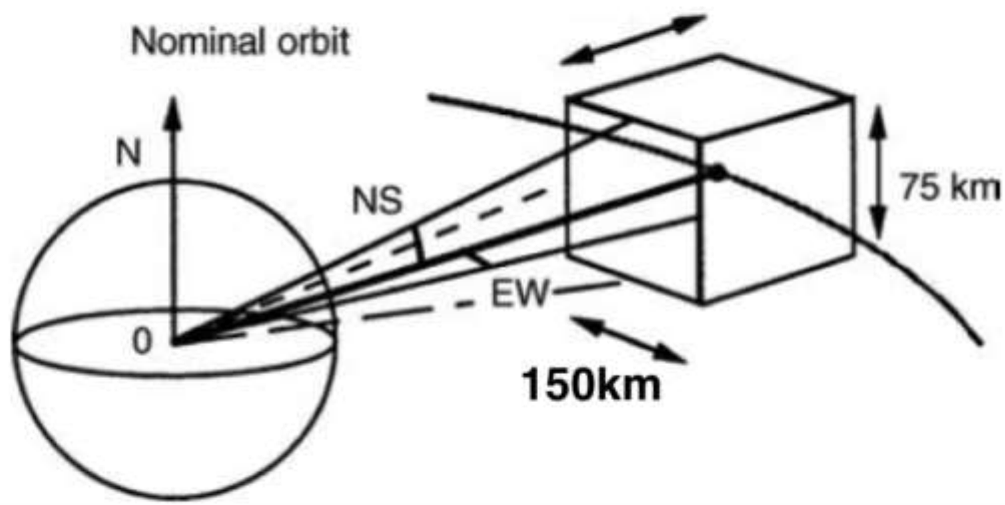




Communication Satellites
East-West Correction Period

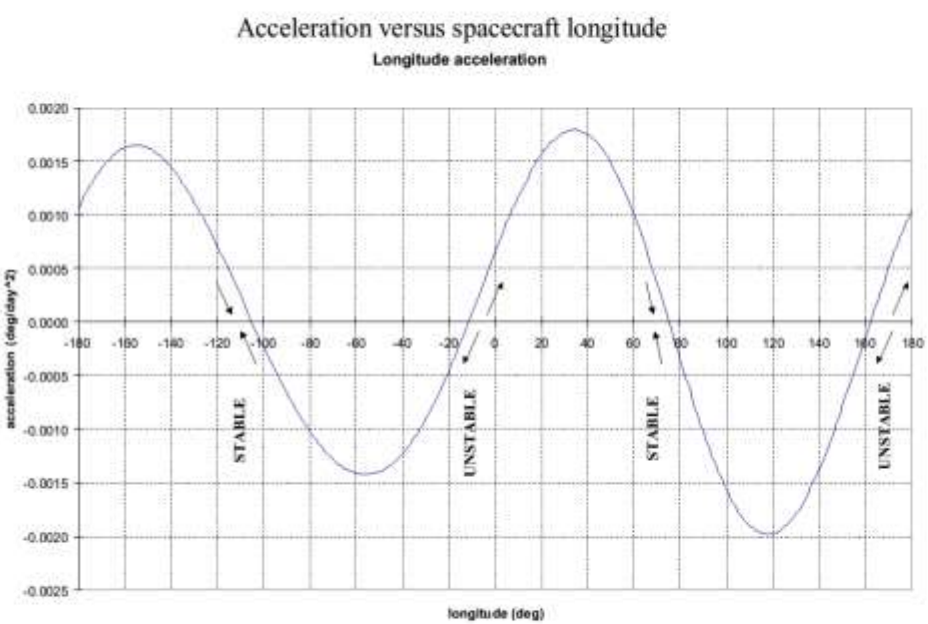
Correction maneuvers are performed to keep the satellite inside a control box.
ITU regulations requires ±0.1° control window at longitude.

1. E/W Control: drift toward stable points need to be corrected.
2. N/S Control: yearly ~0.85 degree inclination



Communication Satellites
DV for Longitude Drift

Non-uniform gravity distribution of Earth results 75 East and 105.3 West stable points. GEO satellites moves toward the closest stable point. Acceleration at 42 degree east is 0.00171 degree/day^2. Yearly required Delta-V can be calculated as below. Earth rotation per day (24 hours) is 361 degree.



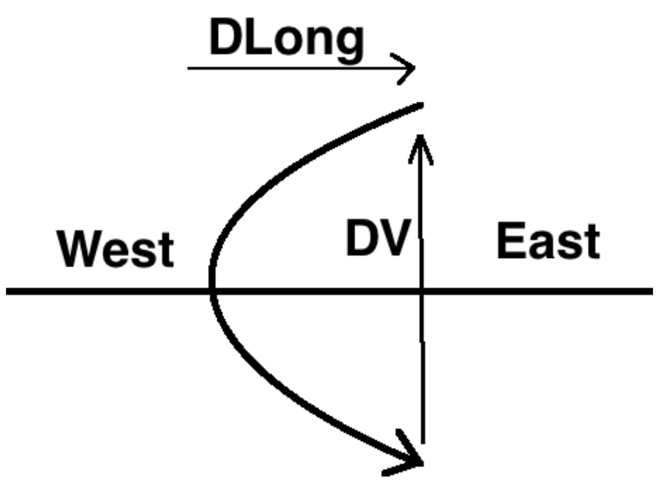
$$DV_T = V_{GEO} \cdot \frac{a_L .365}{3W_E}$$

$$DV_T = 3074x \frac{0.00171x365}{3x361}$$

$$DV_T = 1.78\, m/s$$

Communication Satellites
Orbit East-West Correction Period

- Acceleration at 42 degree east is 0.00171 degree/day^2.
- 14 days maneuver period provides 0.04 degree, remaining margin left for eccentricity control and errors



$$\mathrm{D}Long = \frac{1}{2} a_L \left(\frac{T_C}{2}\right)^2 = \frac{a_L . T_C^2}{8}$$

$$\mathrm{D}Long = \frac{0.00171 x 14^2}{8} = 0.042$$

Communication Satellites Eccentricity Perturbation

- Solar Pressure increases the eccentricity. Eccentricity oscillates longitude with 2e magnitude (in radians).
- Eccentricity magnitude is proportional to surface to mass ratio of the satellite
- Negligible in propellant budget calculations

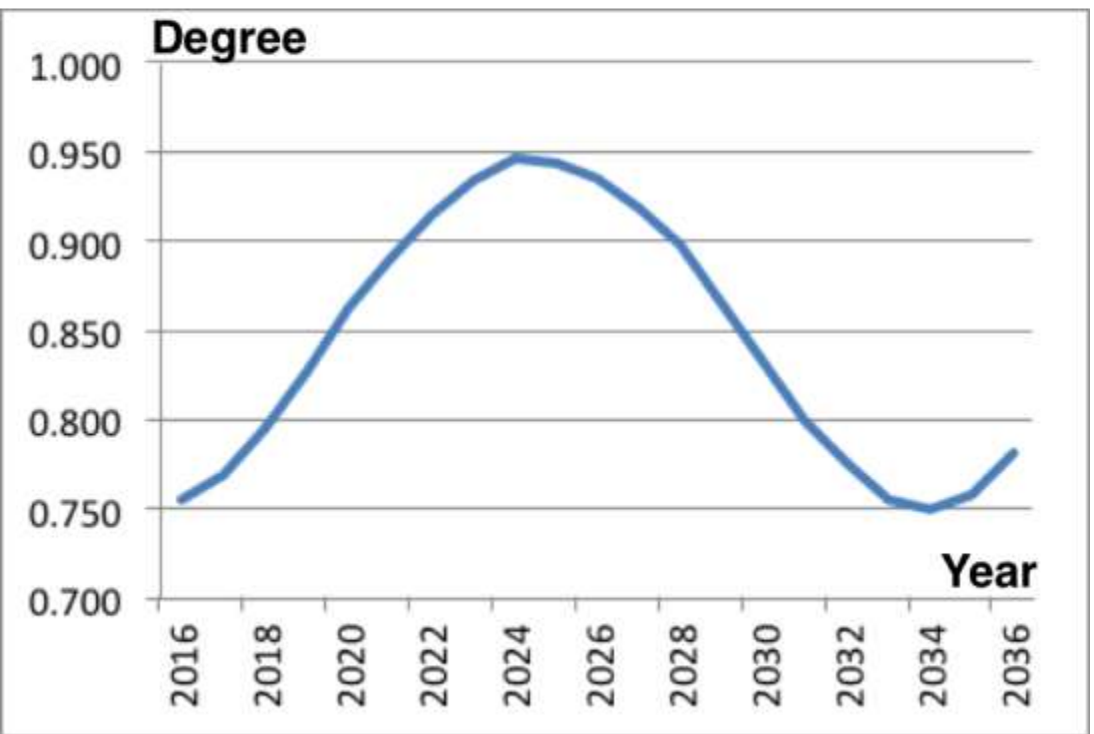
$$e_n \text{ » } 0.0166 \frac{S}{M} (radians)$$

$$S \text{ » } 44.0 m^2, M = 1283 kg$$

$$e_n = 0.000569 \, (radians), DLong = 2e = 0.065^o$$

Communication Satellites Inclination Perturbation

23.4 degree between equatorial and ecliptic plane causes inclination at GEO satellites. Yearly inclination effect changes 0.75-0.95 degree. Delta V required is proportional to inclination change. Average yearly 0.85 inclination change can be corrected with 45.6 m/s Delta-V



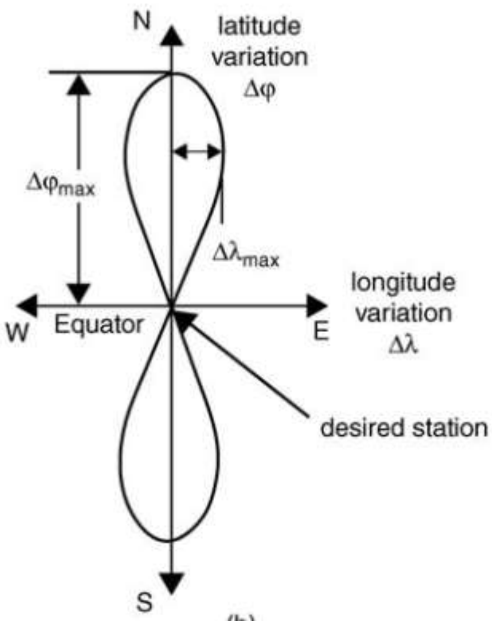
$$DV_i = V_{GEO}.Di\ (i\ radians)$$

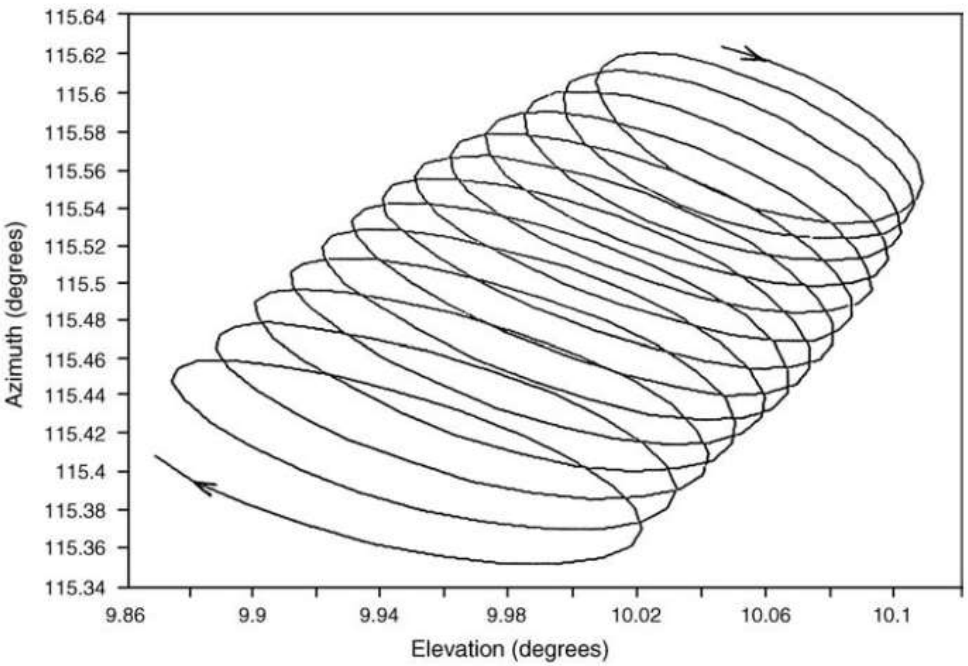
$$DV_i = 3074x0.85$$

$$DV_i = 45.6\ m/s$$

Communication Satellites
Overall Effect of Perturbations

Satellite draws shape “8” by excluding longitude drift. Overall effect is a helix spiral moving to the stable longitude position.
Example satellite drifts toward 105 West





Communication Satellites Platform-Propellant Budget

- Propellant budget is an important analysis in satellite design. North-South delta V is 45.6 m/s/year and East-West Delta V is 1.78 m/s/year.
- Starting from an initial mass we reach to dry mass by subtracting propellant masses required for DV changes.

Lifetime	20	years			
Maneuver	DeltaV (m/s)	Isp (sec)	Efficiency	Delta M (kg)	Mass (kg)
					3067.9
AMF	1487.8	321	0.99	1164.59	1903.3
N/S	912	286	0.92	566.68	1336.6
E/W	35.6	286	0.86	19.58	1317.0
Propellant Mass				1750.86	
Dry Mass				1317.04	

Satellite Communication
Digital Communication

- Today, all satellite communication is digital
- TV broadcasting started digital since year 2000's
- Satellite television mostly DVB-S2 or old DVB-S standards.
- TV broadcasting used phase modulation: QPSK, 8PSK

Türksat 3A/4A/5B © LyngSat, last updated 2024-01-25 - https://www.lyngsat.com/Turksat-3A-4A-5B.h

Frequency Beam EIRP (dBW)	System SR FEC	Logo SID	*Provider Name* Channel Name		ONID-TID Compression Format	VPID	C/N lock Audio	Encryption
10955 H tp 20 West	DVB-S2 8PSK 4444 3/4		(feeds)					
10959 V tp 8 West 52	DVB-S2 8PSK 6250 5/6	TRT	***TRT***		65535-1		9.4	
		23	**TRT Arabi**	S	MPEG-4/HD	611	631 Ara	
		10605	**TRT World**	S	MPEG-4/HD	1605	1705 Eng 1805 Eng	
10962 H tp 20 West	DVB-S2 8PSK 4444 5/6		(feeds)					
10967 V tp 8 West 52	DVB-S2 8PSK 7918 5/6	TRT	***TRT***		65280-0		9.4	BISS
		1	(TRT feeds)			3000	3001	BISS
		25	(TRT Spor feeds)			516	542	BISS
		26	(TRT Haber feeds)			514	1705	BISS
		1001	**TRT 2**		MPEG-4/HD	888	256 Tur	BISS

DVB-S2

- **Digital Video Broadcasting** - Satellite - Second Generation (DVB-S2) is a digital television broadcast standard that has been designed as a successor for the popular DVB-S system.
- It was developed in 2003 by the Digital Video Broadcasting Project, an international industry consortium, and **ratified by ETSI (EN 302307) in March 2005.**
- The standard is based on, and improves upon DVB-S and the electronic news-gathering (or Digital Satellite News Gathering) system, used by mobile units for sending sounds and images from remote locations worldwide back to their home television stations.
- **DVB-S2 is designed for broadcast services including standard and HDTV, interactive services including Internet access, and (professional) data content distribution**

DVB-S2

- Data
- Encoder
- Modulator
- Channel
- Demodulator
- Decoder
- Data

ETSI EN 302 307 V1.1.1 (2005-03)

European Standard (Telecommunications series)

**Digital Video Broadcasting (DVB);
Second generation framing structure, channel coding and modulation systems for Broadcasting, Interactive Services, News Gathering and other broadband satellite applications**

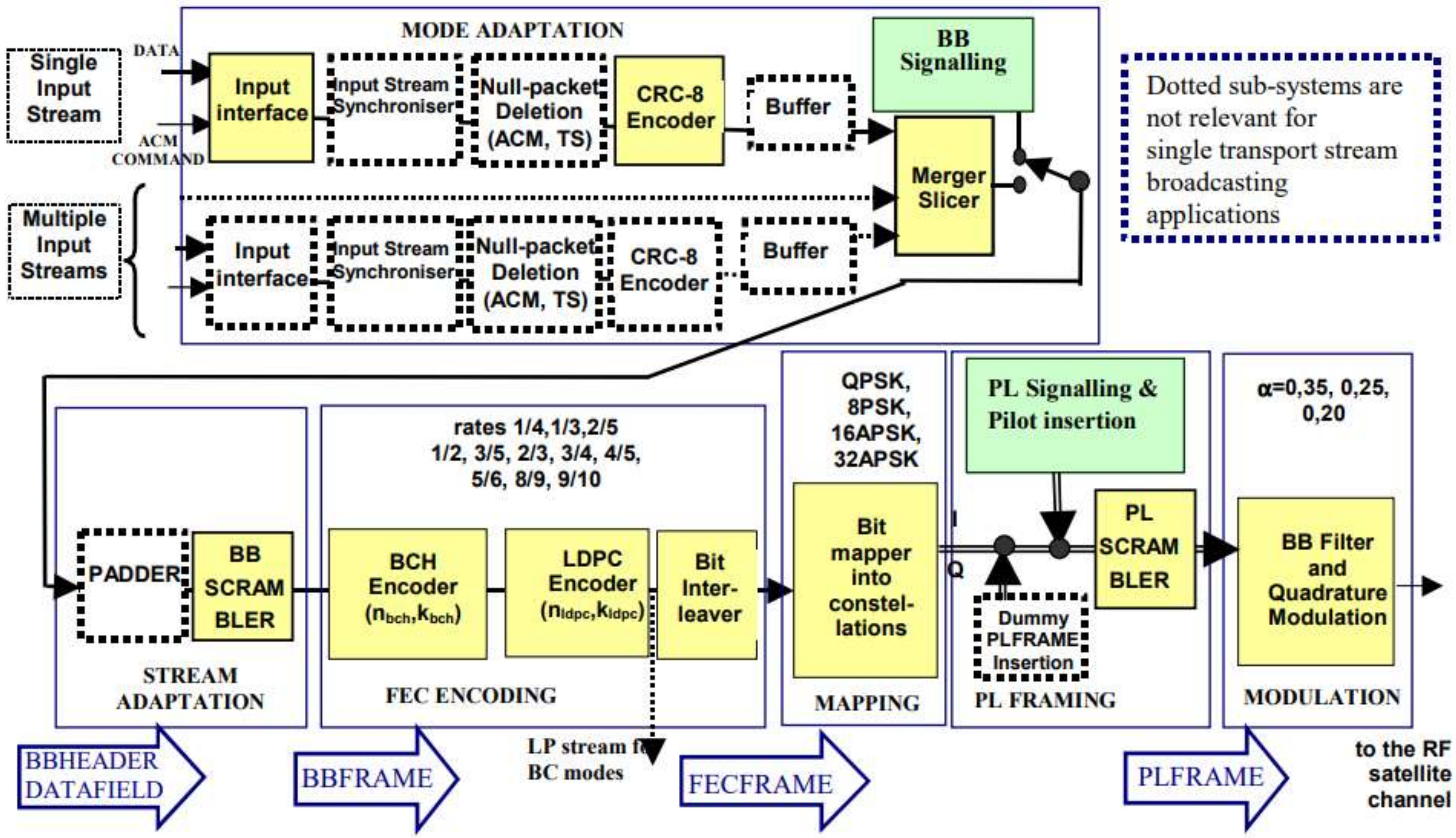
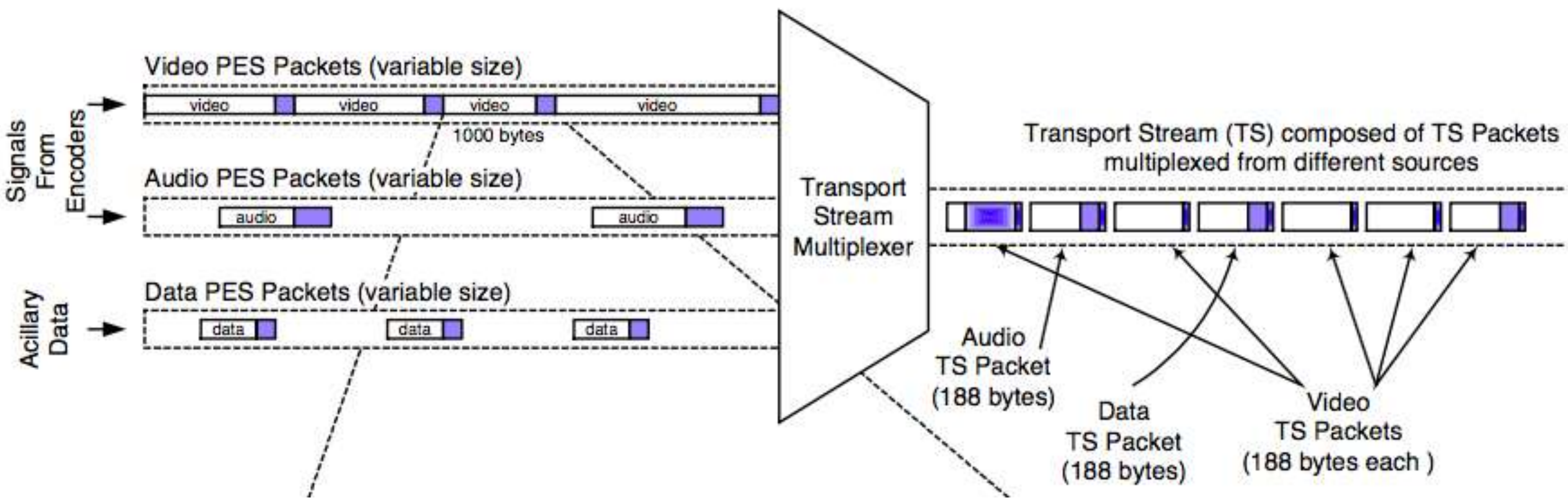


Figure 1: Functional block diagram of the DVB-S.2 System

Satellite Communication
MPEG TS

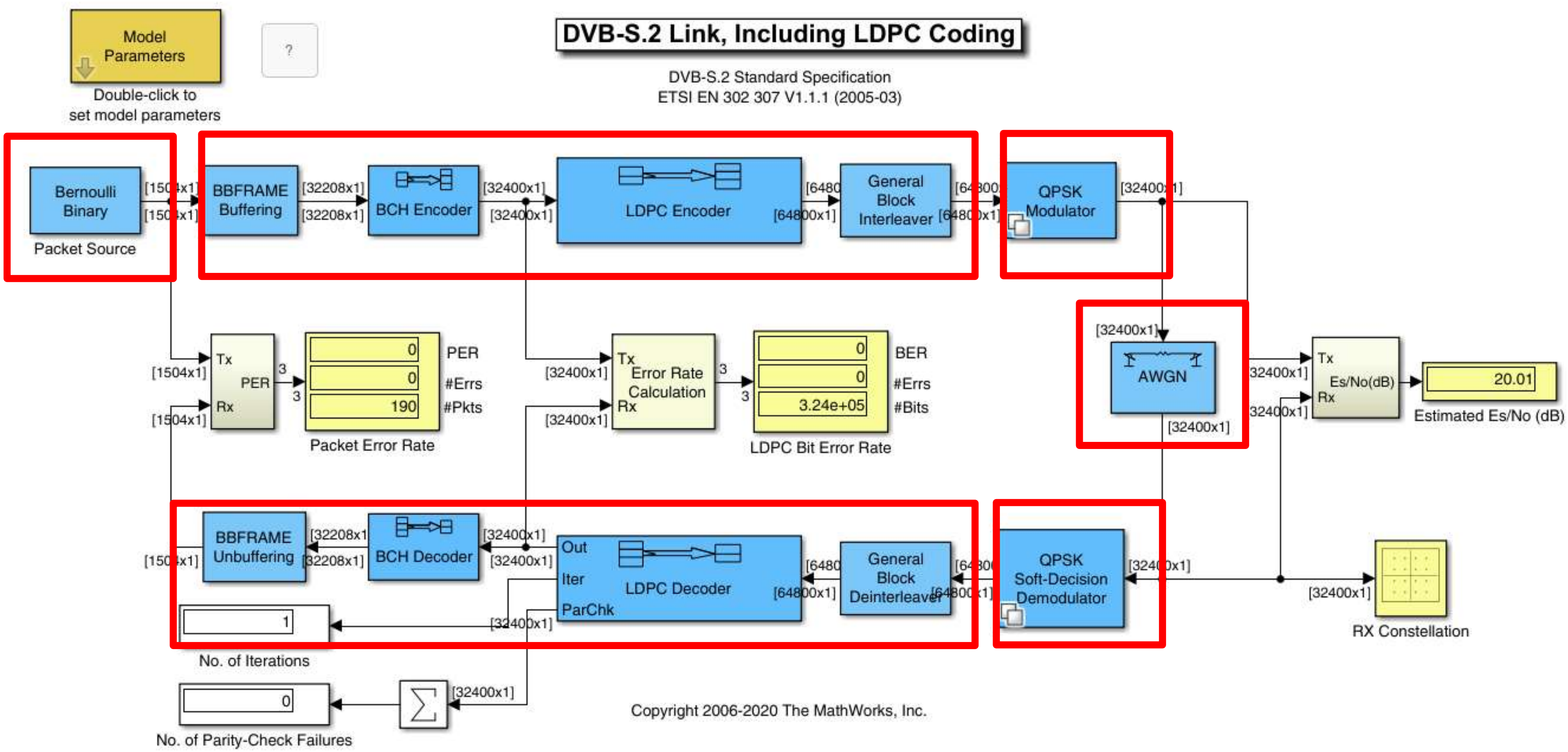
- MPEG (Moving Picture Experts Group) Packetized Elementary Stream (PES) packets are multiplexed to 188 byte (1504 bits) Transport Stream (TS) packets which may have video, audio or data.



DVB-S2

- Data
- Encoder
- Modulator
- Channel
- Demodulator
- Decoder
- Data

>> openExample('comm/DVBS2LinkIncludingLDPCCodingSimulinkExample')

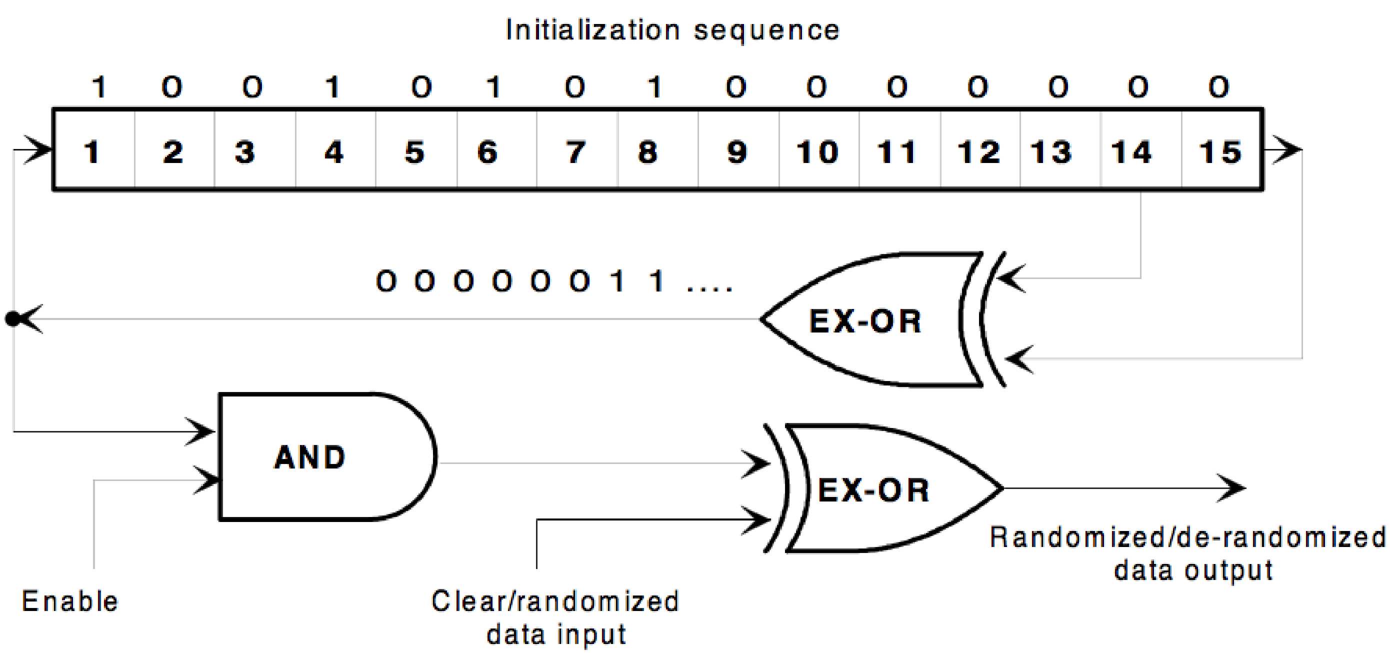


Forward Error Correction

- forward error correction (FEC) or channel coding is a technique used for **controlling errors** in data transmission over unreliable or noisy communication channels.
- The central idea is that the sender encodes the message in a redundant way, most often by using an error correction code or error correcting code (ECC).
- The redundancy allows the receiver not only to detect errors that may occur anywhere in the message, but often to correct a limited number of errors**. Therefore a reverse channel to request re-transmission may not be needed. The cost is a fixed, higher forward channel bandwidth.**
- Forward Error Correction (FEC) Encoding shall be carried out by the **concatenation of BCH outer codes and LDPC (Low Density Parity Check)**
- inner codes (rates 1/4, 1/3, 2/5, 1/2, 3/5, 2/3, 3/4, 4/5, 5/6, 8/9, 9/10).

Scrambler

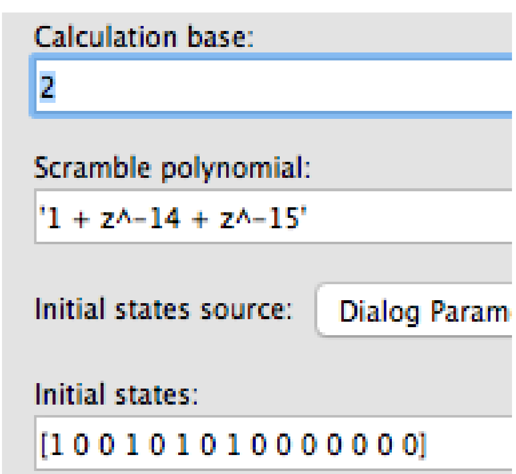
- The total packet length of the MPEG-2 transport Multiplex (MUX) packet is 188 bytes. This includes 1 sync-word byte (i.e. 47HEX).
- Randomizer (Scrambler) removes possibility of periodic or consecutive ones or zeros.

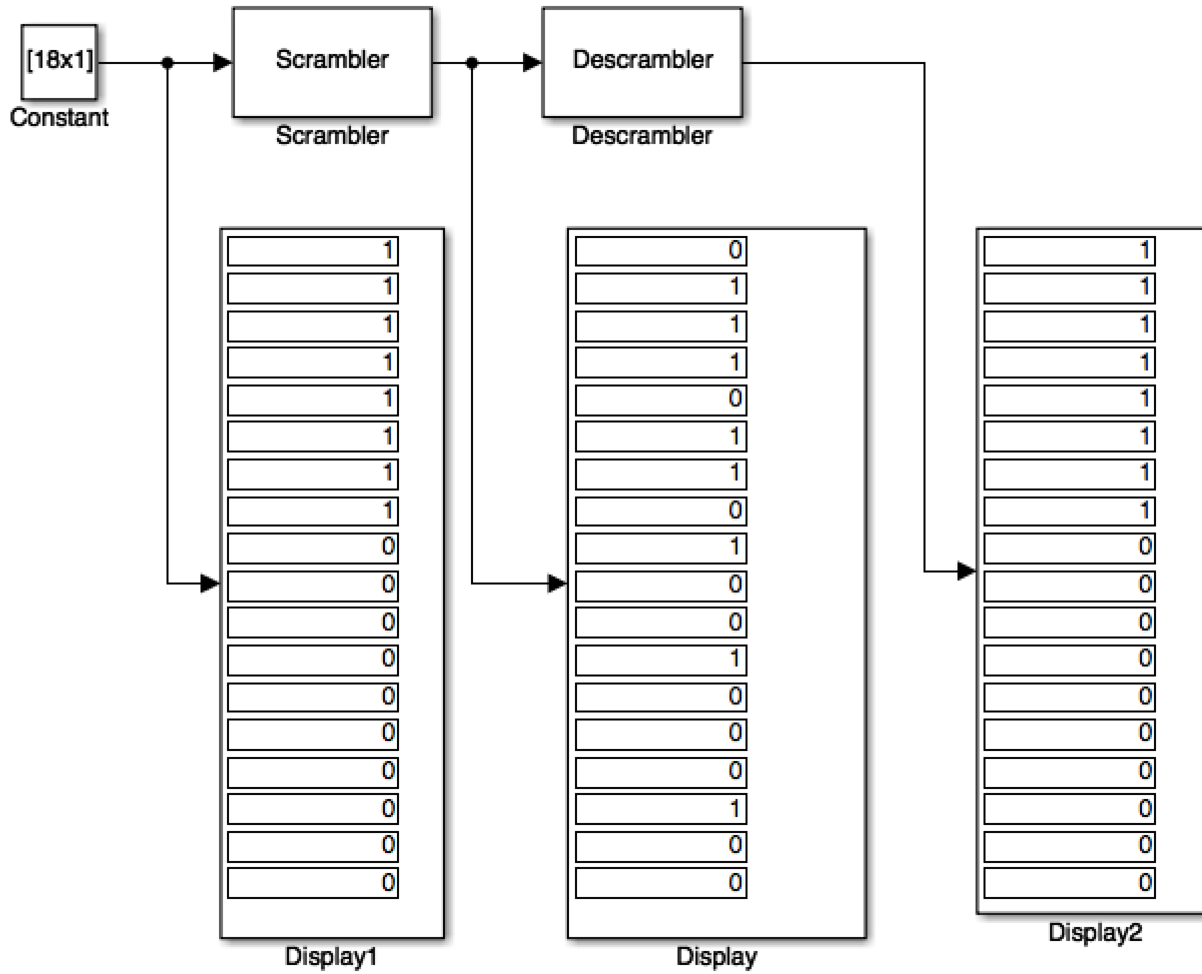


Scrambler

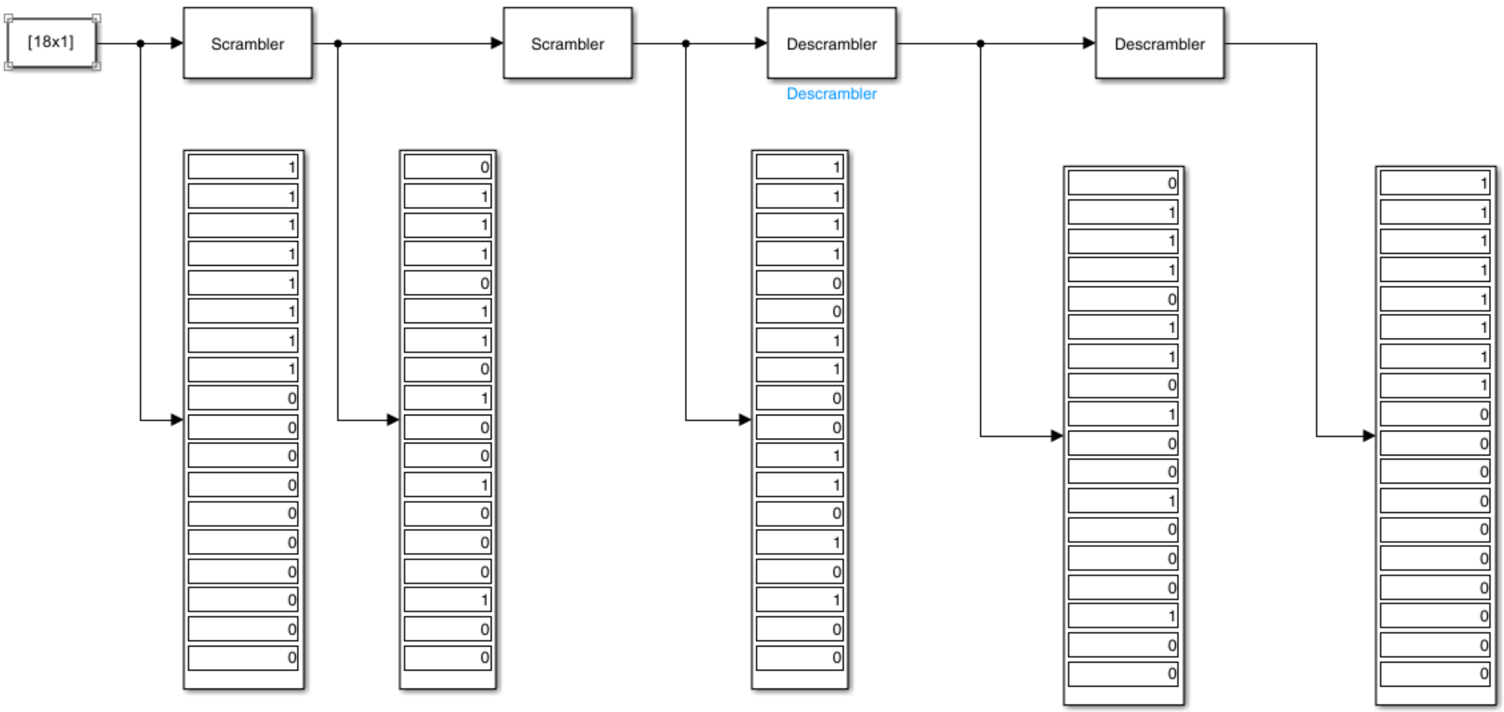
purpose of scrambling is to reduce the length of s of 0s or 1s in a transmitted signal, since a long of 0s or 1s **may cause transmission synchronization problems.**

What happens if not ???





Scrambler-Scrambler is Working



BCH Codes

- Data
- Encoder
- Modulator
- Channel
- Demodulator
- Decoder
- Data

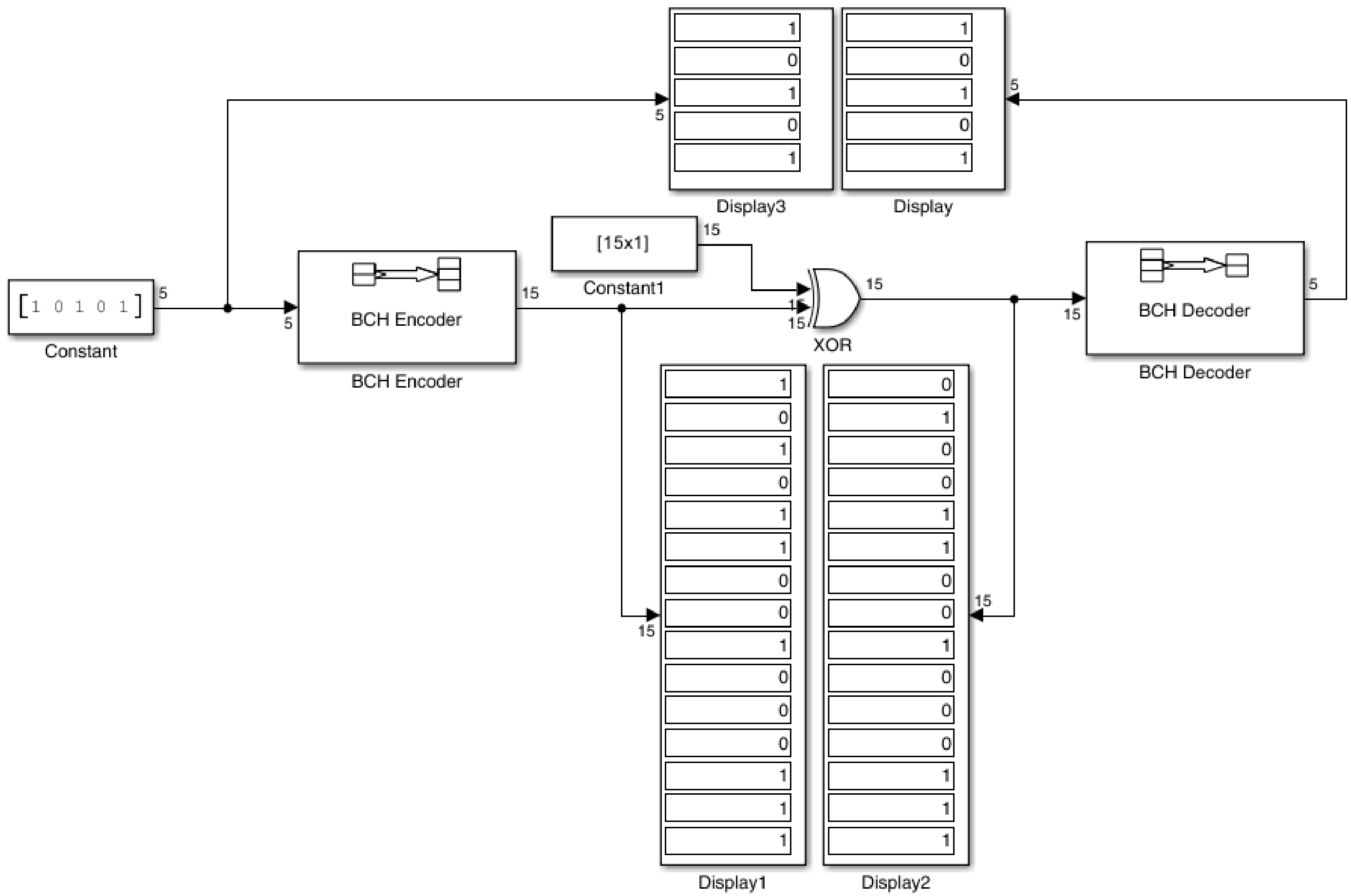
- **BCH (Bose-Chaudhuri-Hocquenghem)** codes are a class of error-correcting codes that are widely used in digital communication systems.

- These codes provide strong **error-detection and error-correction** capabilities.

- **BCH codes** were independently discovered by mathematicians Raj Bose, D. K. Ray-Chaudhuri, and Alexis Hocquenghem in the early 1960s.

BCH Codes

- 5 bit input data encoded to 15 bits and decoded to 5 bit again
- first 3 bits error generated with XOR gate
- 3bit error is corrected at output
- bchnumerr(15,5), gives 3, means (15,5) can correct up to 3 bits of error



- Data
- Encoder
- Modulator
- Channel
- Demodulator
- Decoder
- Data

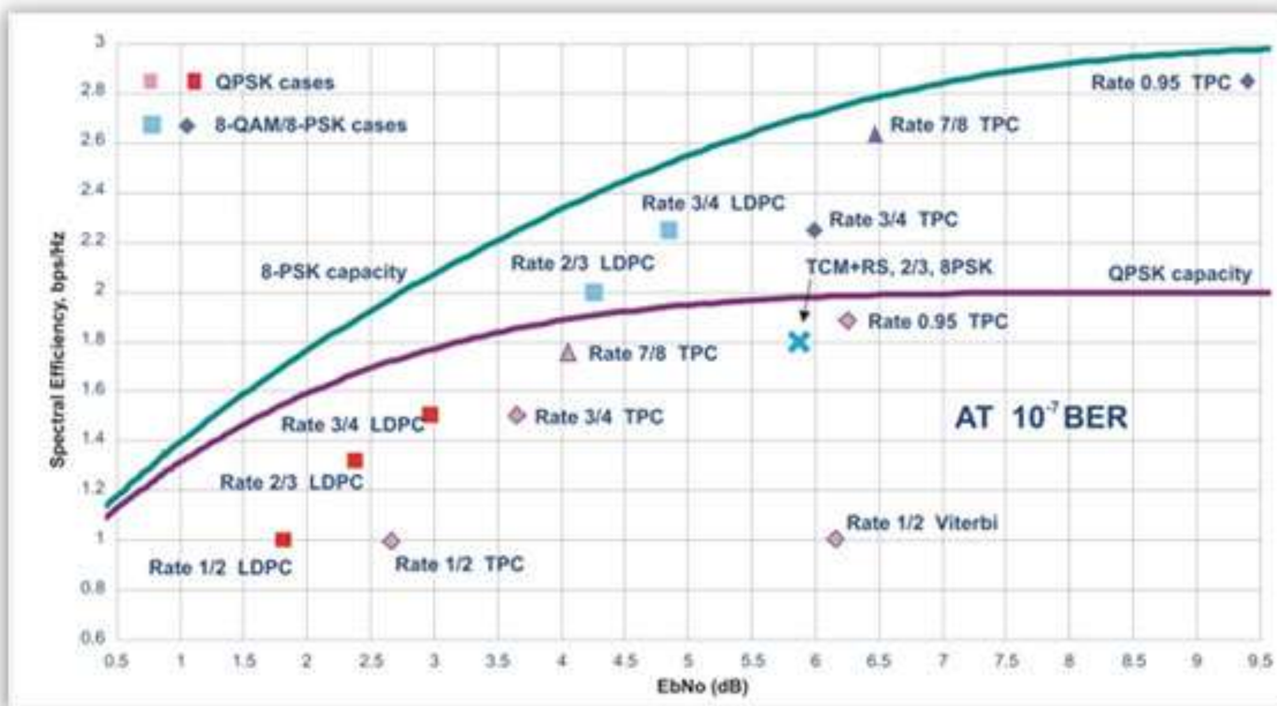
LDPC Codes

- Data
- Encoder
- Modulator
- Channel
- Demodulator
- Decoder
- Data

- LDPC codes are also known as Gallager codes, in honor of Robert G. Gallager, who developed the LDPC concept in his doctoral dissertation at the Massachusetts Institute of Technology in 1960.[4][5]
- However, LDPC codes require computationally expensive iterative decoding, so they went unused for decades.
- In 1993 the newly invented turbo codes demonstrated that codes with iterative decoding could far outperform other codes used at that time, but **turbo codes were patented and required a fee for use**. This raised renewed interest in LDPC codes, which were shown to have similar performance, but were much older and patent-free.
- Now that the fundamental patent for turbo codes has expired (on August 29, 2013), LDPC codes are still used for their technical merits.

LDPC Codes

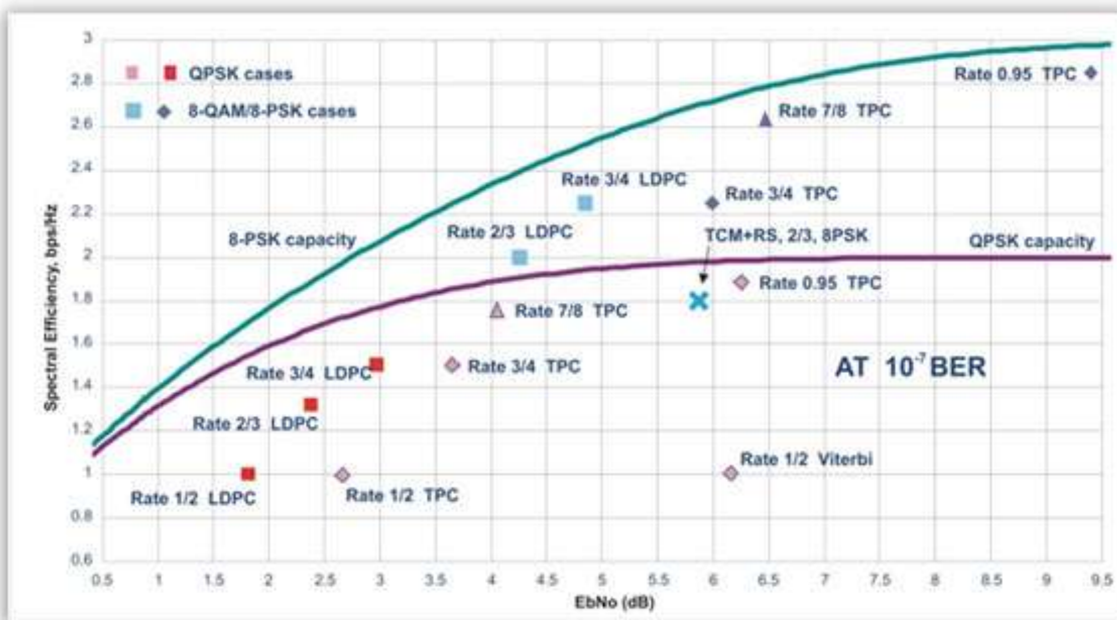
- Low-Density Parity-Check Codes enable near **Shannon limit performance**. LDPCs were originally proposed in 1962, but only recently regained attention. LDPCs are coded according to sparse parity-check matrixes and decoded using iterative algorithms similar to that of turbo decoding. Based on recent research, LDPCs were found to have the potential to offer both better performance and lower decoding complexity in many cases. In fact, an irregular rate R=1/2 LDPC with block length of 107 currently holds the record of best FEC performance, 0.04 dB to the Shannon limit at BER level of 10-6 in an AWGN channel. The chart below illustrates the relative performance of LDPC:



Shannon Limit

- The Shannon–Hartley theorem states the **channel capacity C (bps)** meaning the theoretical tightest upper bound on the information rate of data that can be communicated at an arbitrarily low error rate using an average received signal power S through an analog communication channel subject to additive white Gaussian noise (AWGN) of power (N)
- How can you increase the capacity:
    - increase the bandwidth
    - increase signal power
    - reduce noise

$$\boxed{C \leq B * log_2 \ (1 + S/N)}$$



Satellite Communication Bandwidth-Shannon Limit

- Given a bandwidth, what is the maximum data rate can we transmit ?
- Shannon-Hartley theorem is the answer.

- C: data rate , bps
- B: Bandwidth, Hz
- S/N Signal to Noise ratio

$$C < B \times log_2\left(1 + \frac{S}{N}\right)$$

given S/N=20 dB convert it to linear value
xdB = 10 log (x), x= 10^ xdB/10
S/N=20dB, B=1MHz, C=?
C=1M * log2(1+ 10^(20/10)
C=1M * log2(101)
C= 6.6 Mbps

[Shannon–Hartley theorem - Wikipedia]

LDPC Codes

- Data
- Encoder
- Modulator
- Channel
- Demodulator
- Decoder
- Data

LDPC code with a 1/2 rate for illustration:

- Message: **111011**
- Let's use a 6x12 parity-check matrix for a 1/2 rate LDPC code:

1 1 0 0 0 0 1 0 0 0 0 0
0 1 1 0 0 0 0 1 0 0 0 0
0 0 1 1 0 0 0 0 1 0 0 0
0 0 0 1 1 0 0 0 0 1 0 0
0 0 0 0 1 1 0 0 0 0 1 0
0 0 0 0 0 1 1 0 0 0 0 1

- generate the parity bits. xor mi if there is 1, and xor the remaing bits of each row
- p1p2p3p4p5p6=101001

$$p_1 = m_1 \oplus 0 \oplus 1 \oplus 0 \oplus 0 \oplus 0 \oplus 1 = 1 \oplus 0 \oplus 1 \oplus 0 \oplus 0 \oplus 0 \oplus 1 = 1$$

$$p_2 = m_2 \oplus 0 \oplus 0 \oplus 1 \oplus 1 \oplus 0 \oplus 0 = 0 \oplus 0 \oplus 1 \oplus 1 \oplus 0 \oplus 0 = 0$$

$$p_3 = m_3 \oplus 0 \oplus 0 \oplus 0 \oplus 0 \oplus 1 \oplus 0 = 1 \oplus 0 \oplus 0 \oplus 0 \oplus 0 \oplus 1 \oplus 0 = 1$$

$$p_4 = m_3 \oplus m_5 \oplus 0 \oplus 0 \oplus 0 \oplus 1 \oplus 0 = 1 \oplus 1 \oplus 0 \oplus 0 \oplus 0 \oplus 1 \oplus 0 = 0$$

$$p_5 = m_1 \oplus m_6 \oplus 0 \oplus 0 \oplus 0 \oplus 0 \oplus 1 = 1 \oplus 0 \oplus 0 \oplus 0 \oplus 0 \oplus 0 \oplus 1 = 0$$

$$p_6 = m_2 \oplus m_4 \oplus 0 \oplus 0 \oplus 0 \oplus 0 \oplus 1 = 0 \oplus 0 \oplus 0 \oplus 0 \oplus 0 \oplus 0 \oplus 1 = 1$$

- This is the final codeword is info + parity=**111011** 101001

LDPC Codes

- Data
- Encoder
- Modulator
- Channel
- Demodulator
- Decoder
- Data

LDPC code with a 1/2 rate for illustration:

- Message: **111011**
- Let's use a 6x12 parity-check matrix for a 1/2 rate LDPC code:

1 0 0 0 0 0 0 1 0 0 0 1
0 1 0 0 0 0 0 0 1 1 0 0
0 0 1 0 0 0 1 0 0 0 1 0
0 0 1 0 1 0 0 0 0 1 0 0
1 0 0 0 0 1 0 0 0 0 1 0
0 1 0 1 0 0 0 0 0 0 0 1 generate the parity bits. xor mi if there is 1, and xor the remaining bits of each row

- p1p2p3p4p5p6=101001

$$p_1 = m_1 \oplus 0 \oplus 1 \oplus 0 \oplus 0 \oplus 0 \oplus 1 = 1 \oplus 0 \oplus 1 \oplus 0 \oplus 0 \oplus 0 \oplus 1 = 1$$

$$p_2 = m_2 \oplus 0 \oplus 0 \oplus 1 \oplus 1 \oplus 0 \oplus 0 = 0 \oplus 0 \oplus 1 \oplus 1 \oplus 0 \oplus 0 = 0$$

$$p_3 = m_3 \oplus 0 \oplus 0 \oplus 0 \oplus 0 \oplus 1 \oplus 0 = 1 \oplus 0 \oplus 0 \oplus 0 \oplus 0 \oplus 1 \oplus 0 = 1$$

$$p_4 = m_3 \oplus m_5 \oplus 0 \oplus 0 \oplus 0 \oplus 1 \oplus 0 = 1 \oplus 1 \oplus 0 \oplus 0 \oplus 0 \oplus 1 \oplus 0 = 0$$

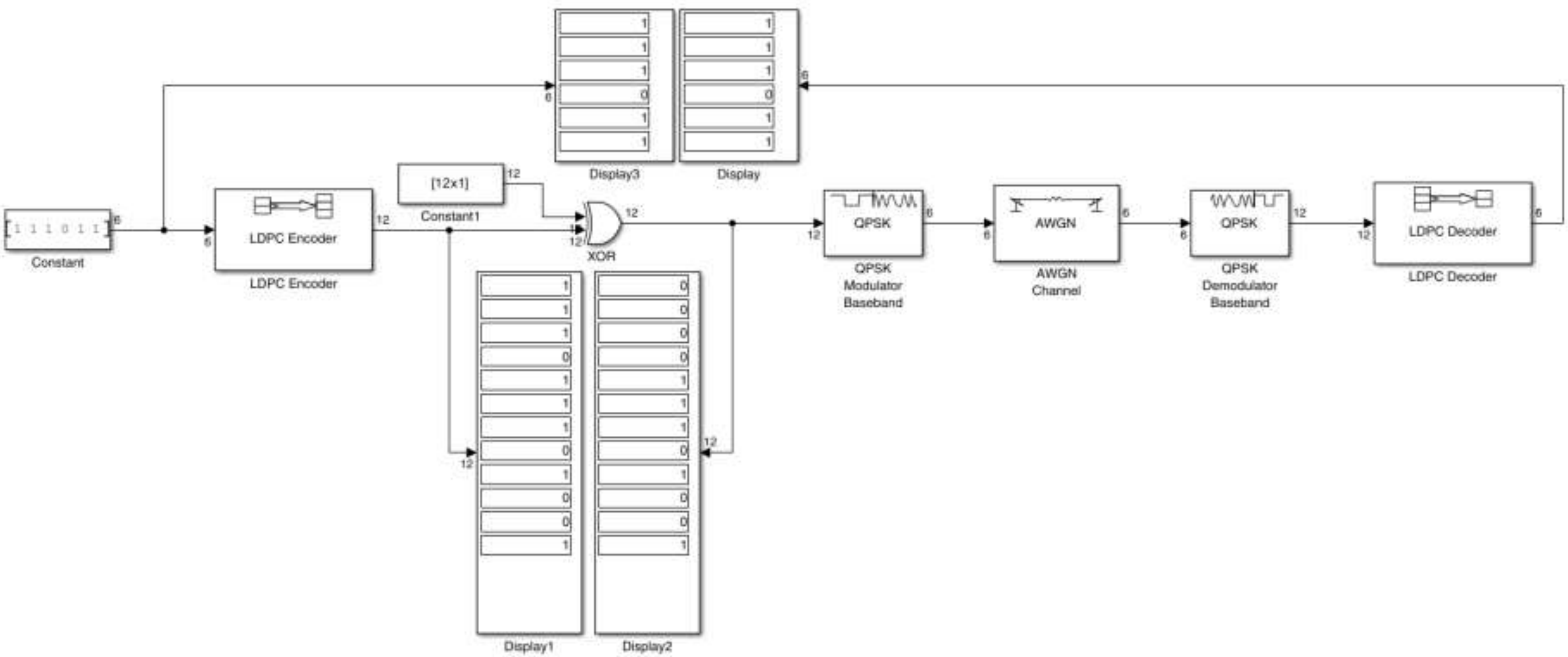
$$p_5 = m_1 \oplus m_6 \oplus 0 \oplus 0 \oplus 0 \oplus 0 \oplus 1 = 1 \oplus 0 \oplus 0 \oplus 0 \oplus 0 \oplus 0 \oplus 1 = 0$$

$$p_6 = m_2 \oplus m_4 \oplus 0 \oplus 0 \oplus 0 \oplus 0 \oplus 1 = 0 \oplus 0 \oplus 0 \oplus 0 \oplus 0 \oplus 0 \oplus 1 = 1$$

- This is the final codeword is info + parity=**111011** 101001

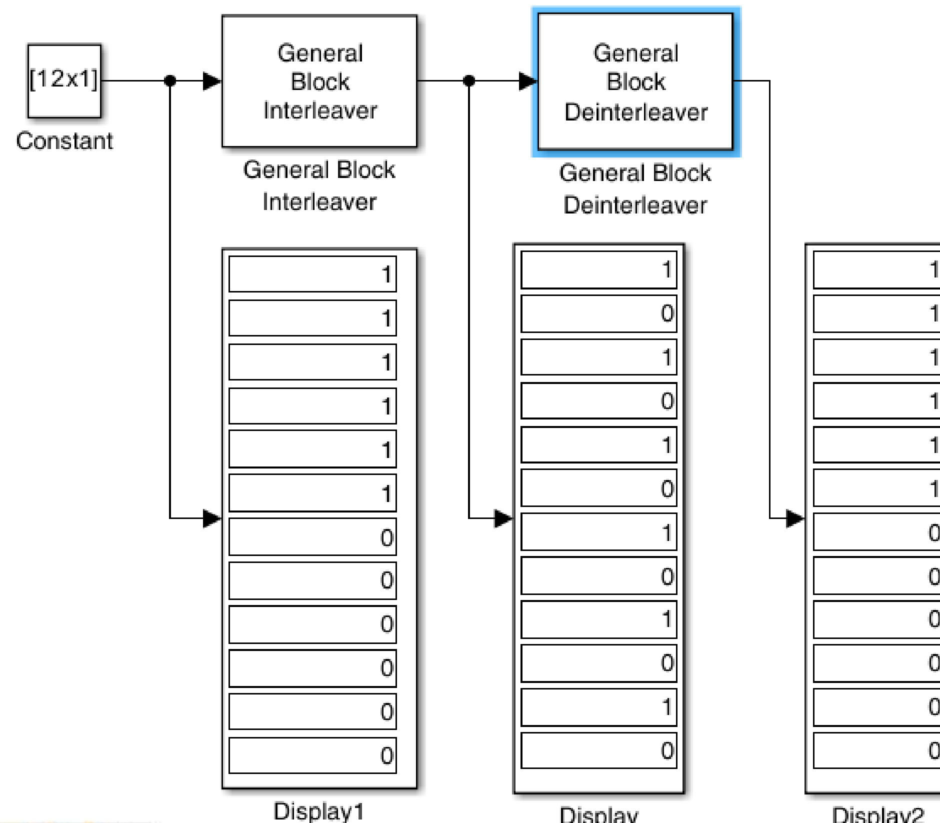
LDPC Codes

- we used QPSK modulator, LDPC decoder needs double input of log-likelihood ratio output of demodulator
- again we can correct 3 bits error



Interleaver

- Description
- The General Block **Interleaver block rearranges the elements of its input vector without repeating or omitting any elements.** If the input contains N elements, then the Permutation vector parameter is a column vector of length N. The column vector indicates the indices, in order, of the input elements that form the length-N output vector;



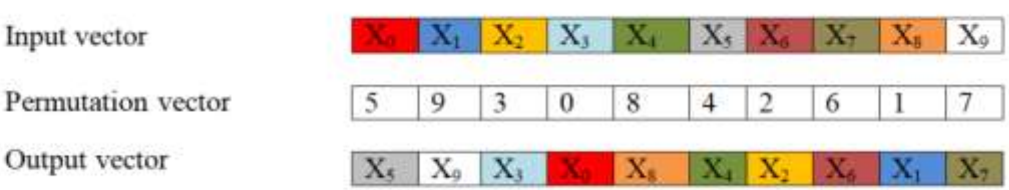
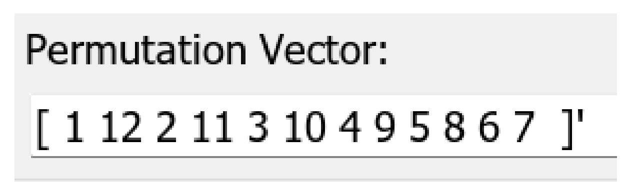


Figure 3. General block interleaver pattern

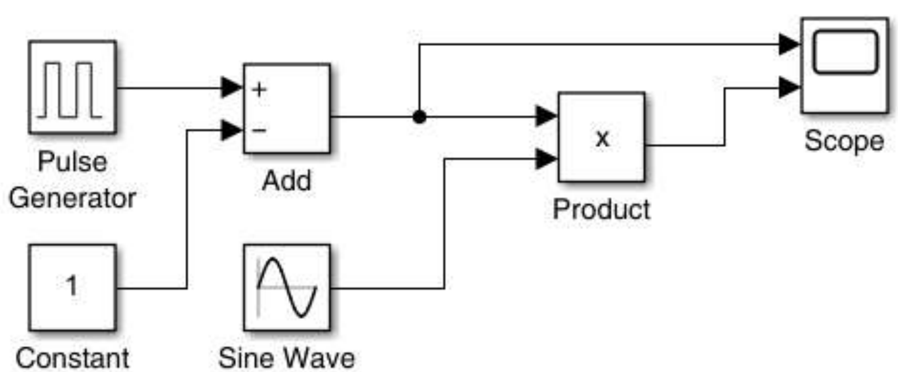


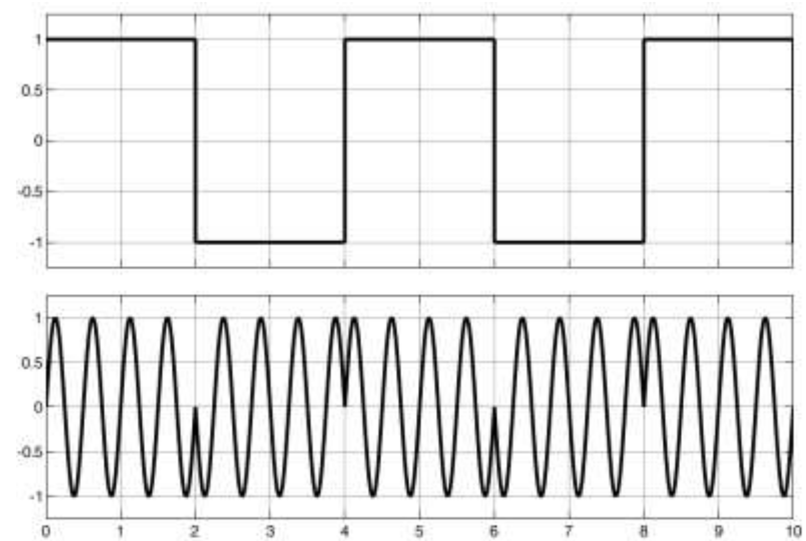
Satellite Communication Phase Modulation-Why?

- Square wave physical signals (like NRZ or other) are low frequency signals and not suitable for RF transmission. Low frequency need higher antenna aperture. Remember gain of the antenna proportional to the frequency.
- Modulation moves the base band (kbps, mbps) signals to sinusoidal form and high frequencies (GHz)
- Modulation may reduce the bandwidth of the baseband signal

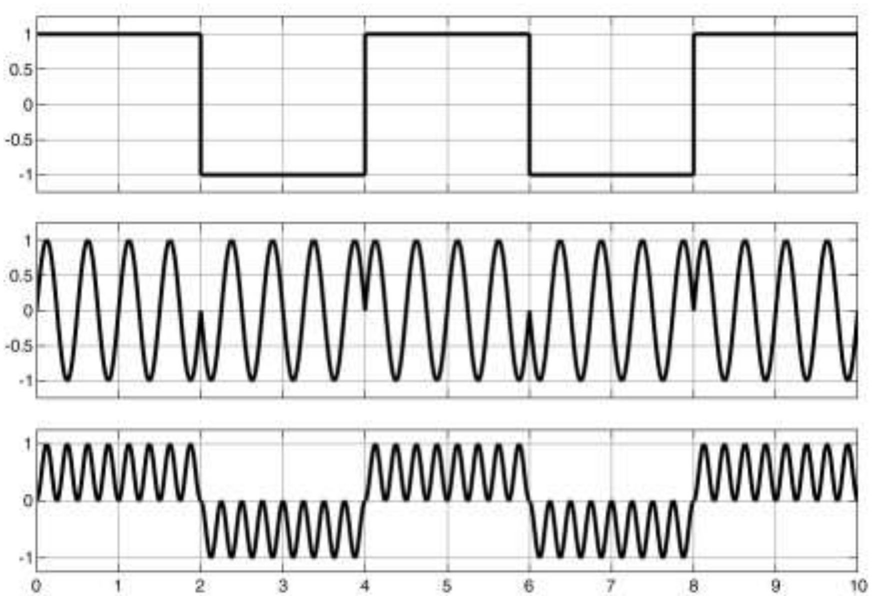
Satellite Communication
Phase Modulation-BPSK

- BPSK, Binary Phase Shift Key is multiplication (mixer) of a sine wave carrier with square wave base band
- Frequency of carrier is equal or higher than the baseband
- Example: baseband 1 bps, carrier 2Hz
- Most of the modems have IF (70MHz or 140MHz) output, means that carrier frequency is 70MHz or 140MHz. Data frequency is in kbps





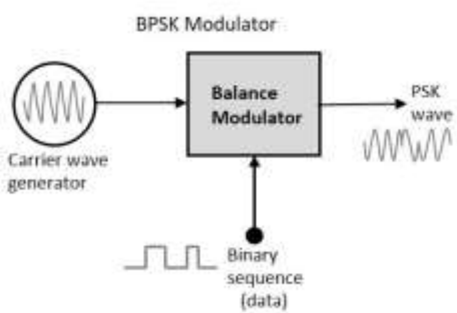
BPSK

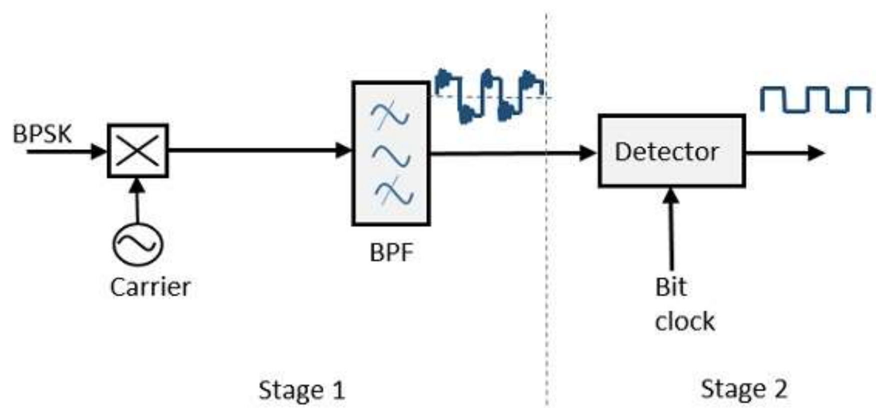


$$A.\cos(wt).\cos(wt)$$
$$= A.cos^2(wt)$$
$$= \frac{A}{2}\{1 + \cos(2wt)\}$$

Band pass filter removes sines above square

BPSK Demodulator

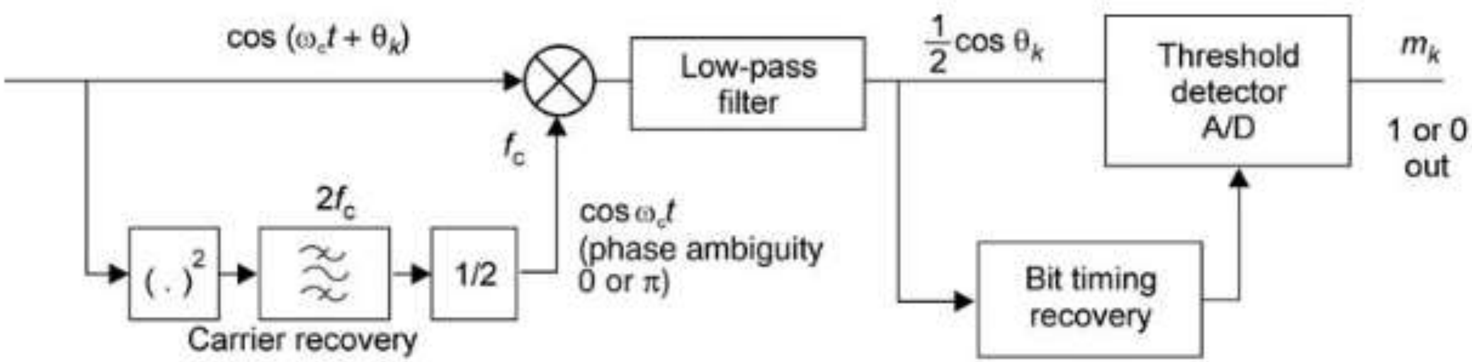




Satellite Communication
BPSK Demodulator

- BPSK Demodulator multiples input with a cosine reference with the same frequency and filters high frequency part. Remaining signal will be either positive cos(0) or negative cos(pi) which can be detected.

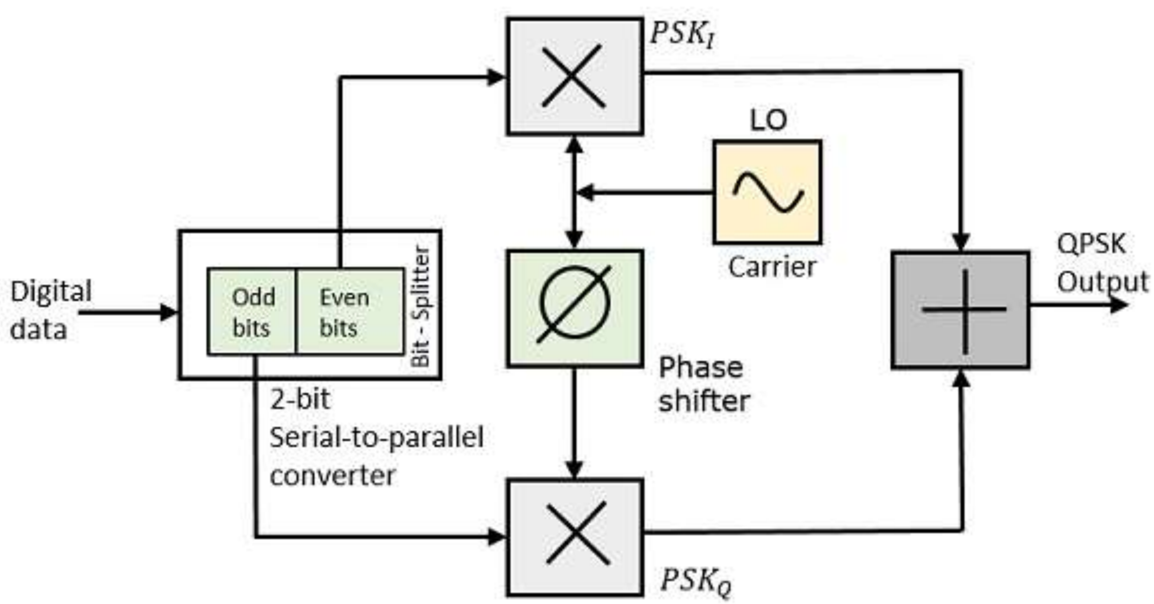
$$
\begin{aligned}
&\cos(w_C t + q_k).\cos(w_C t) \\
&= [\cos(w_C t)\cos(q_k) - \sin(w_C t)\sin(q_k)] x \cos(w_C t) \\
&= \cos^2(w_C t)\cos(q_k) - \sin(w_C t)\cos(w_C t)\sin(q_k) \\
&= \frac{1}{2}(1+\cos(2w_C t))\cos(q_k) - \frac{1}{2}\sin(2w_C t)\sin(q_k) \\
&= \frac{1}{2}\cos(q_k) + \ldots
\end{aligned}
$$



QPSK Modulator

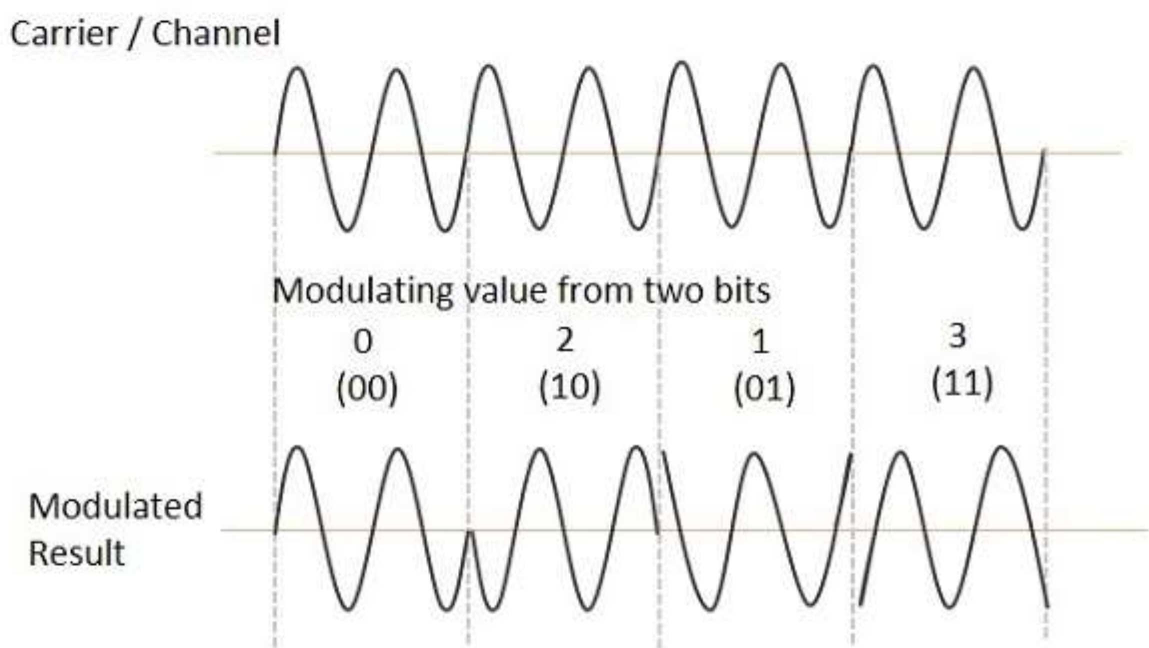
The QPSK Modulator uses a bit-splitter, two multipliers with local oscillator, a 2-bit serial to parallel converter, and a summer circuit.

At the modulator’s input, the message signal’s even bits (i.e., 2nd bit, 4th bit, 6th bit, etc.) and odd bits (i.e., 1st bit, 3rd bit, 5th bit, etc.) are separated by the bits splitter and are multiplied with the same carrier to generate odd BPSK (called as PSKI) and even BPSK (called as PSKQ). The PSKQ signal is anyhow phase shifted by 90° before being modulated.



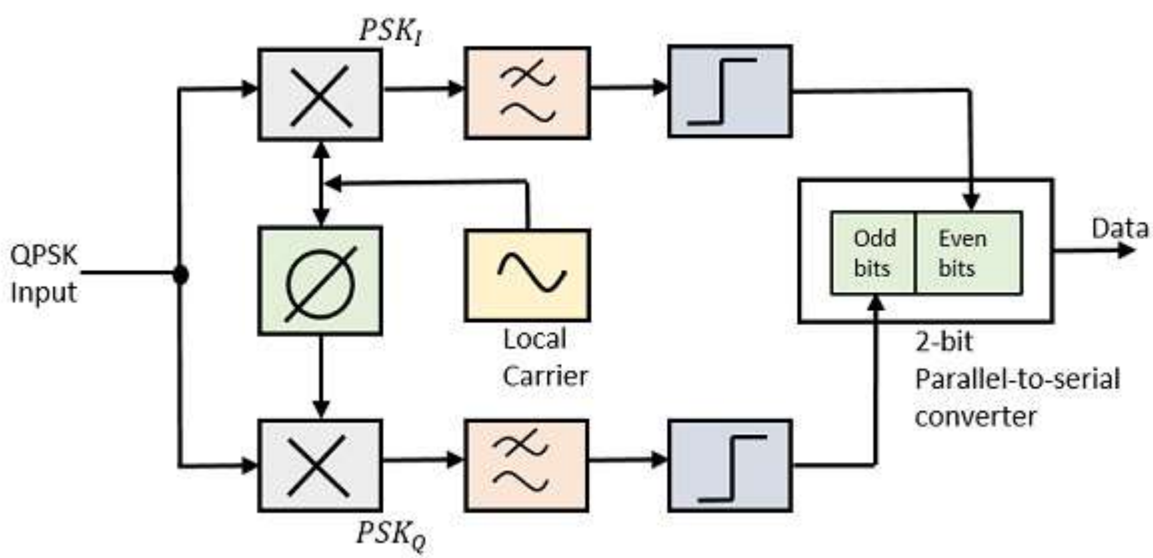
QPSK Modulator

The QPSK waveform for two-bits input is as follows, which shows the modulated result for different instances of binary inputs.



QPSK Demodulator

- The QPSK Demodulator uses two product demodulator circuits with local oscillator, two band pass filters, two integrator circuits, and a 2-bit parallel to serial converter.
- The two product detectors at the input of demodulator simultaneously demodulate the two BPSK signals. The pair of bits are recovered here from the original data.
- These signals after processing, are passed to the parallel to serial converter.



Satellite Communication
Phase Modulation-QPSK

- Phase shifted parts of a cos(wt) used for 11,01,00 and 10 pairs.
- Phase diagram is used to show the phase of QPSK.
- **Gray code** used to allow only 1 bit change between consecutive phase changes. This coding reduces BER.

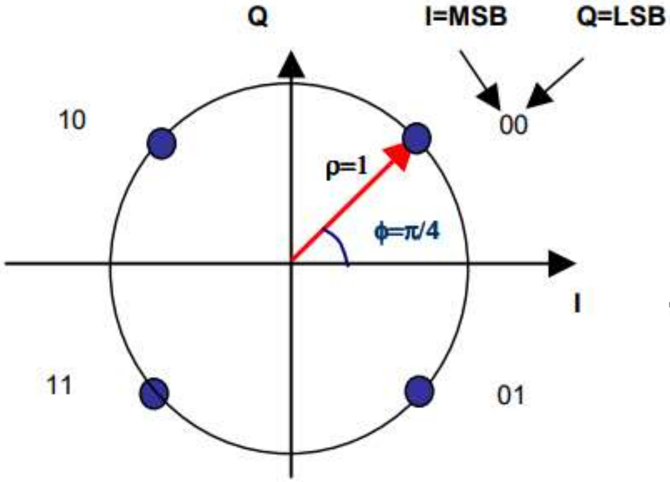
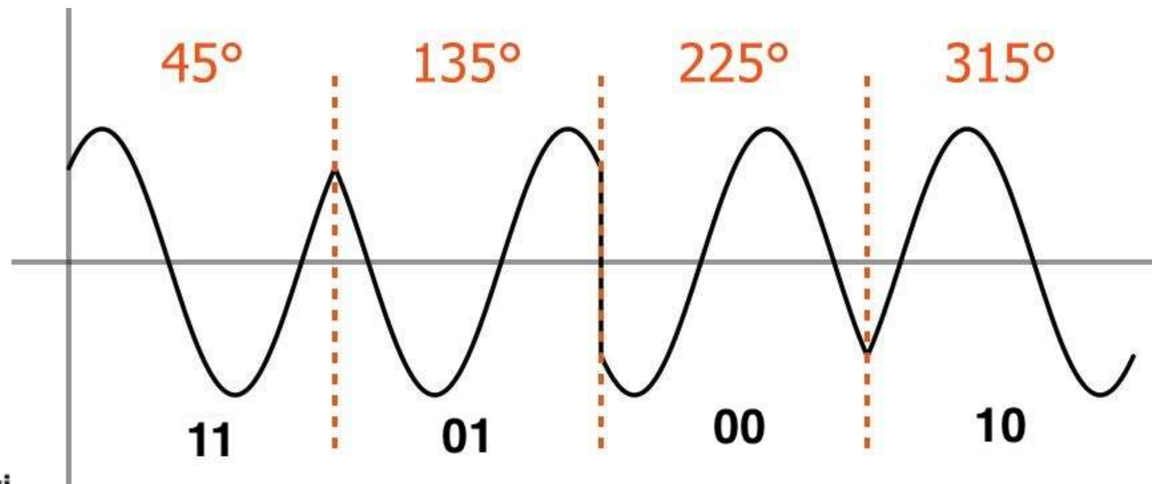
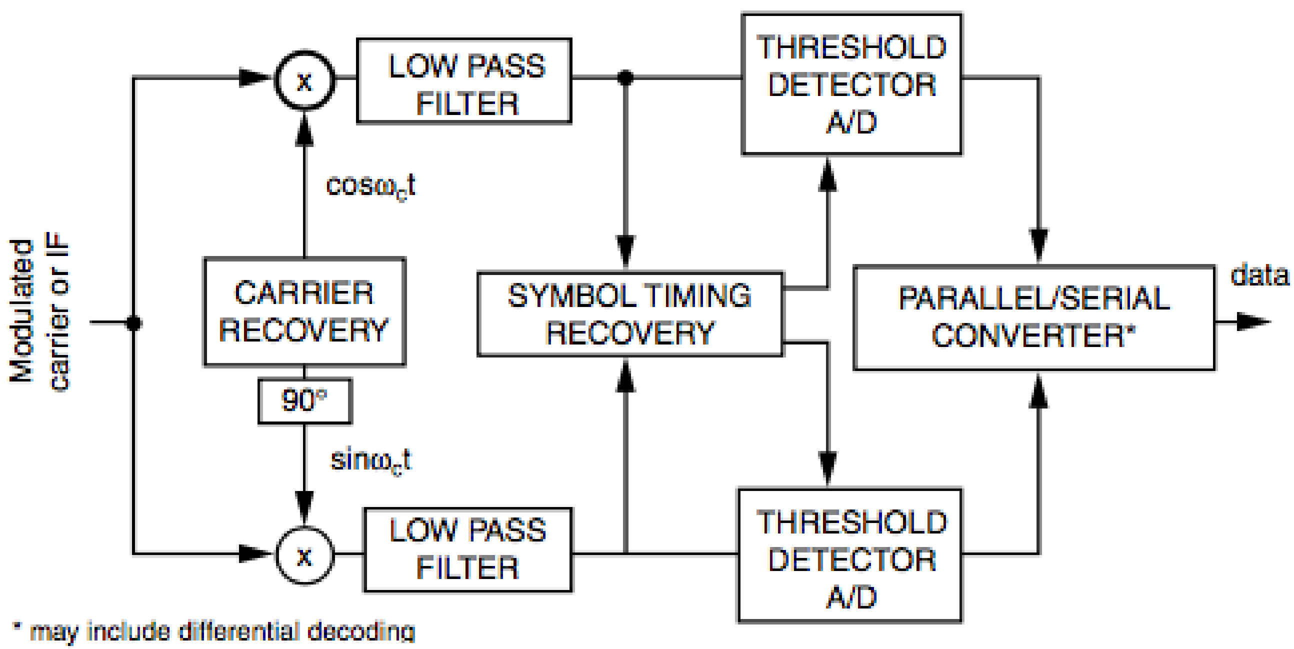


Figure 9: Bit mapping into QPSK constellati



Satellite Communication QPSK Demodulator

- QPSK demodulator consist of two BPSK demodulator each demodulates in-phase and quadarture-phase components and serialize bits.



8PSK

- For 8PSK, the System shall employ conventional Gray-coded 8PSK modulation with absolute mapping (no differential coding).
- Bit mapping into the 8PSK constellation shall follow figure 10.

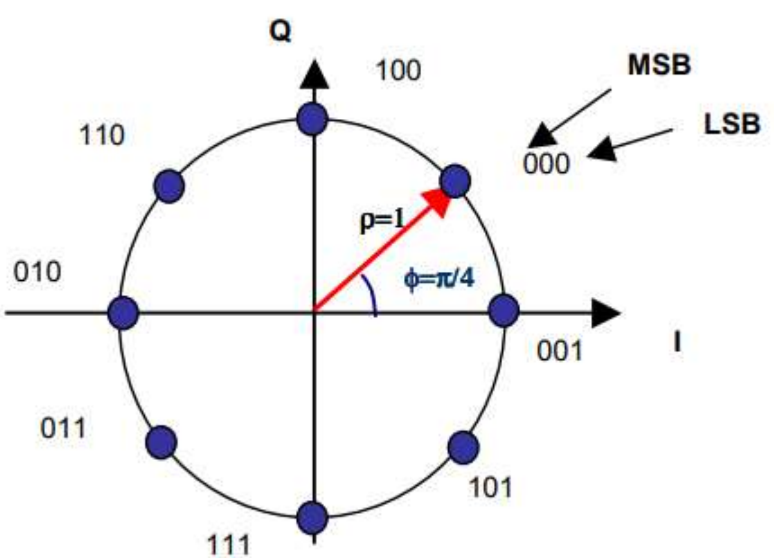
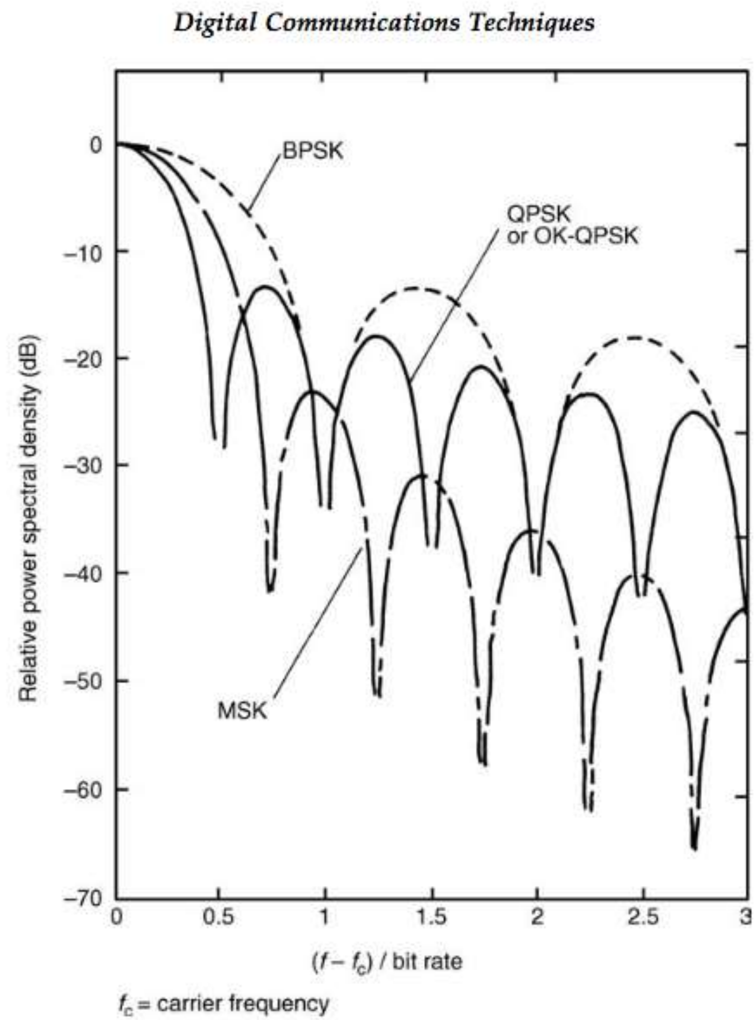


Figure 10: Bit mapping into 8PSK constellation

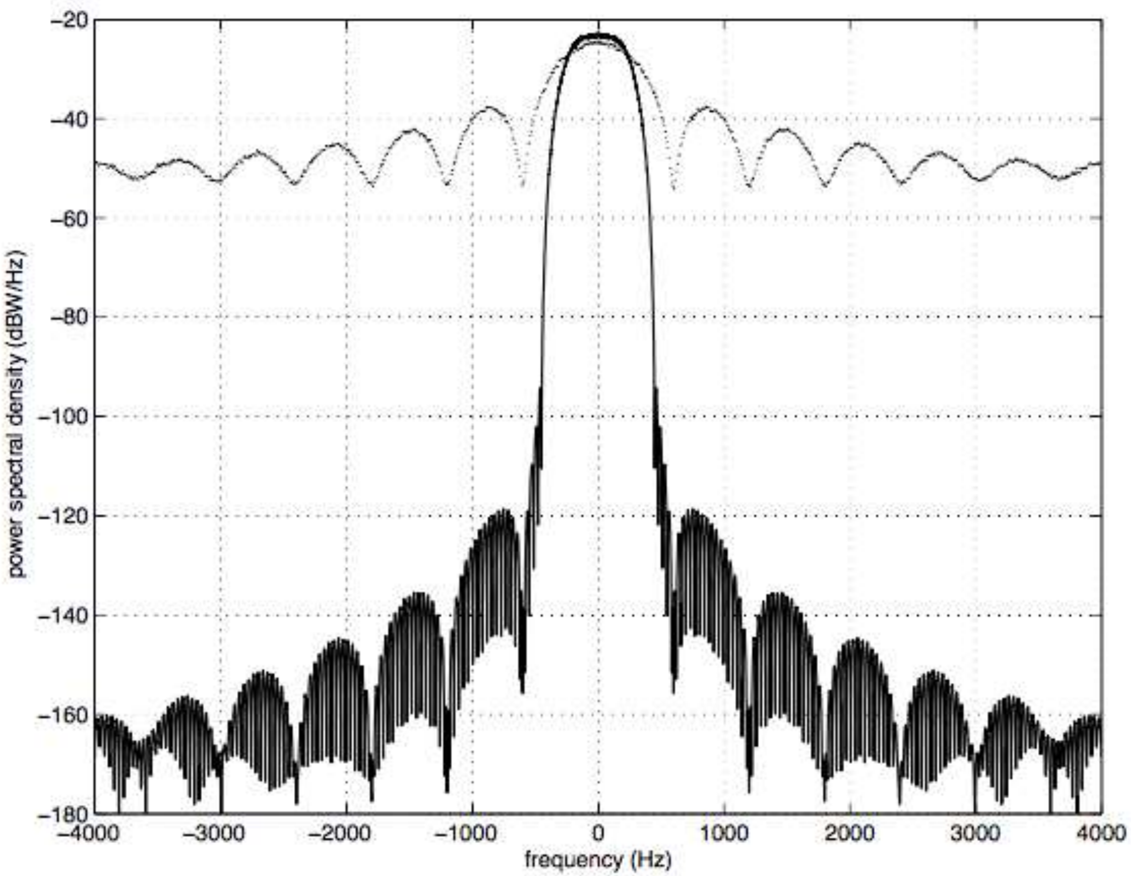
Satellite Communication Phase Modulation-Spectrum

- Note that QPSK main lobe bandwidth is half of the BPSK.
- Spectrum has harmonics which need to be filtered.



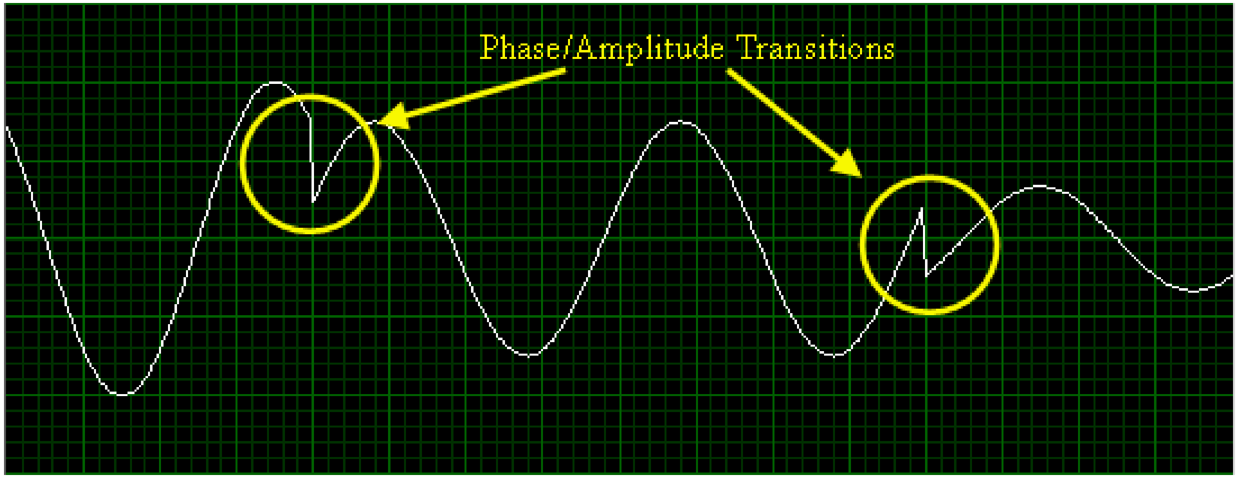
Satellite Communication Phase **Modulation-Raised Cosine**

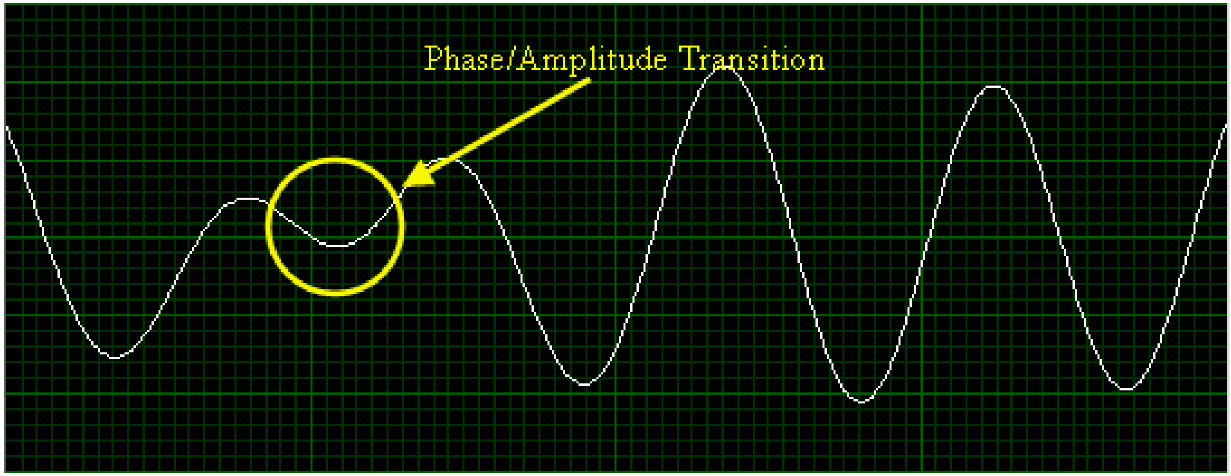
- Bandwidth of the signal is defined by the raised cosine filter. Beta of the filter (roll-off) is defined in DVB-S (0.35), DVB-S2(0.35, 0.25, 0.20) standards



Satellite Communication
Phase Modulation-Filtering

- Filter smoothens spikes in phase transitions,
- reduces harmonics and limits the bandwidth





Satellite Communication
Baseband Shaping and Modulation

- the signals shall be **square root raised cosine** filtered. The roll-off factor shall be **r = 0,35, 0,25 and 0,20**
- Spectrum mask is given is standard

The baseband square root raised cosine filter shall have a theoretical function defined by the following expression:

$$H(f) = 1 \qquad \text{for } |f| < f_N(1-\alpha)$$

$$H(f) = \left\{ \frac{1}{2} + \frac{1}{2}\sin\frac{\pi}{2f_N}\left[\frac{f_N - |f|}{\alpha}\right] \right\}^{\frac{1}{2}} \qquad \text{for } f_N(1-\alpha)$$

$$H(f) = 0 \ \text{ for } |f| > f_N(1+\alpha),$$

where: $f_N = \frac{1}{2T} = \frac{R_s}{2}$ is the Nyquist frequency and α is the roll-off factor.

Satellite Communication
Baseband Shaping and Modulation

- the signals shall be square root raised cosine filtered. The roll-off factor shall be **r = 0,35, 0,25 and 0,20**
- Spectrum mask is given is standard

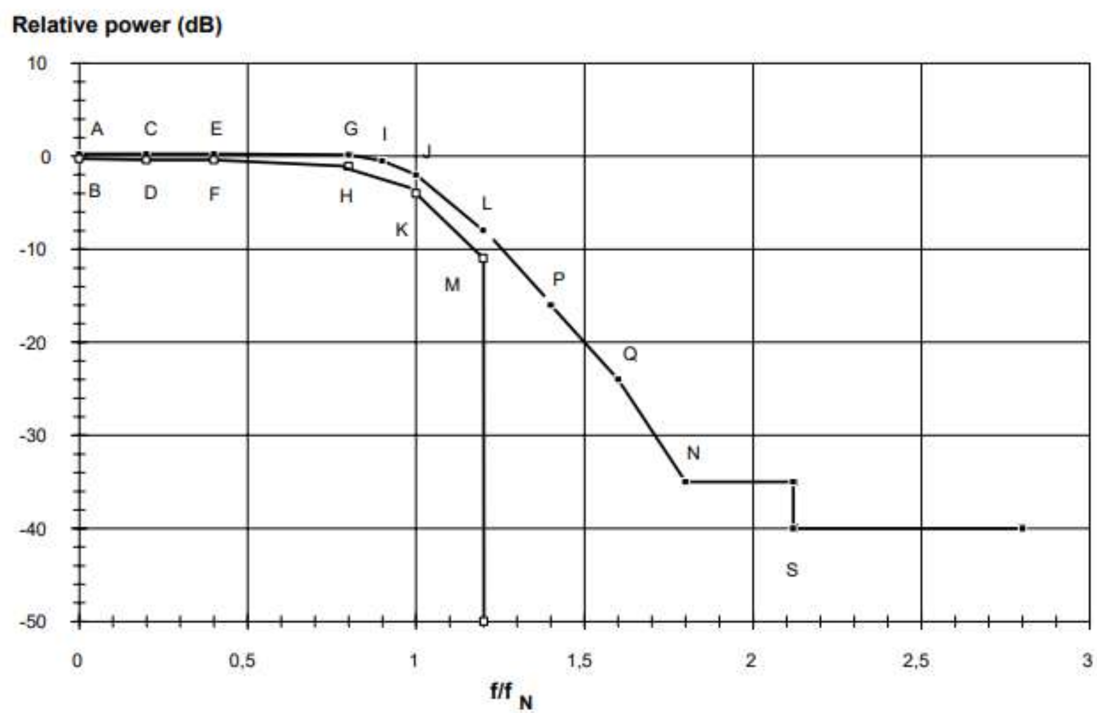
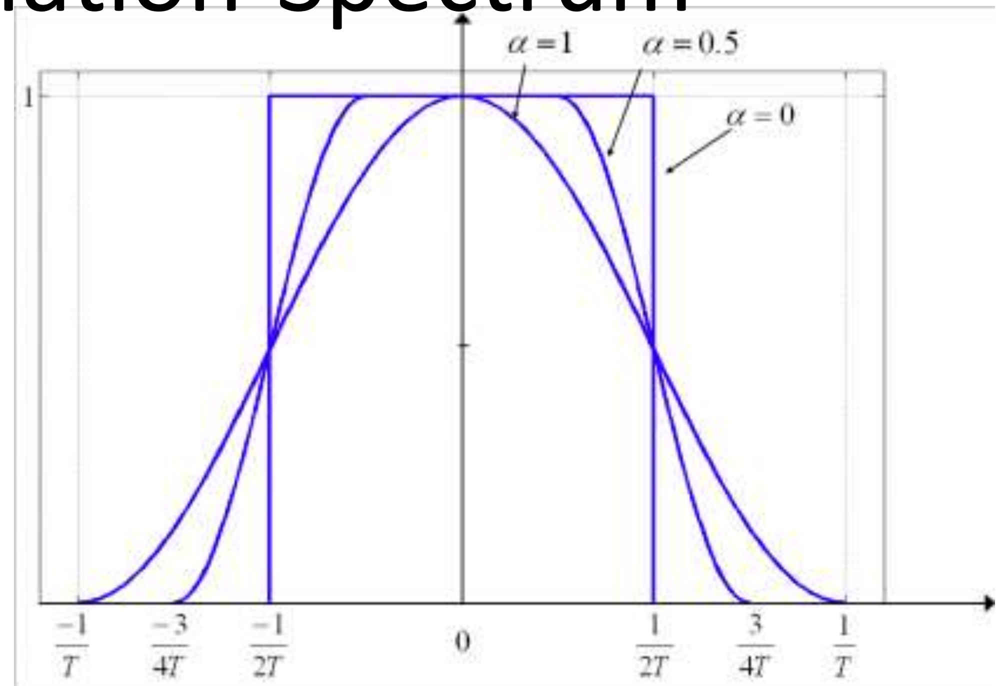


Figure A.1: Template for the signal spectrum mask at the modulator output represented in the baseband frequency domain, the frequency axis is calibrated for roll-off factor α = 0,35

Satellite Communication Phase Modulation-Spectrum

- Square Root Raised cosine filter is used satellite communication



$$H(f) = 1 \qquad \text{for } |f| < f_N(1-\alpha)$$

$$H(f) = \left\{ \frac{1}{2} + \frac{1}{2}\sin\frac{\pi}{2f_N}\left[\frac{f_N - |f|}{\alpha}\right]\right\}^{1/2} \qquad \text{for } f_N(1-\alpha)$$

$$H(f) = 0 \text{ for } |f| > f_N(1+\alpha),$$

Satellite Communication
Phase Modulation-Bandwidth

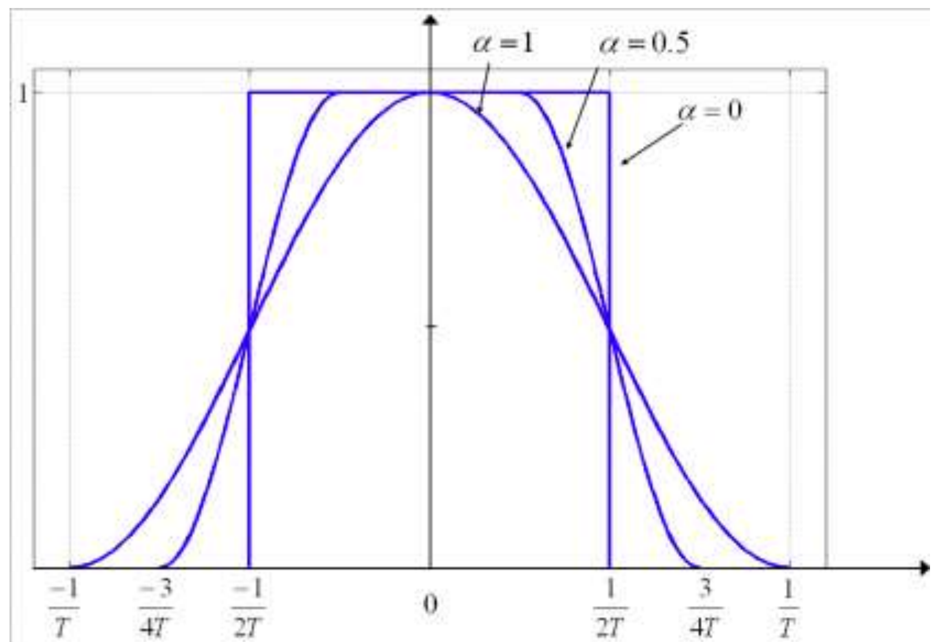
- **Roll-off factor** and symbol rate defines the bandwidth of the filter.
- In BPSK one bit is one symbol but in QPSK two bits is one symbol

$$H(f)=1 \qquad \text{for } |f|<f_N(1-\alpha)$$

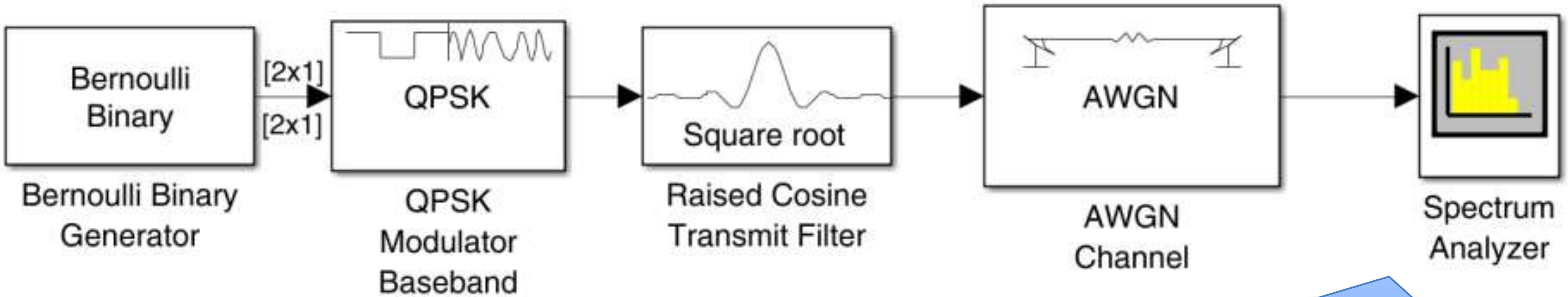
$$H(f)=\left\{\frac{1}{2}+\frac{1}{2}\sin\frac{\pi}{2f_N}\left[\frac{f_N-|f|}{\alpha}\right]\right\}^{1/2} \qquad \text{for } f_N(1-\alpha)$$

$$H(f)=0 \text{ for } |f|>f_N(1+\alpha),$$

$$BW = (1+r)\times Rs$$
$$Ri = Rs \times log_2(M)$$
BW: $bandwidth$
Rs: $symbol\ rate$
Ri: $bit\ rate$
M: $MPSK, 2,4,8$
r: $roll\ off\ factor$



QPSK Bandwidth



$$BW = (1 + r) \times Rs$$

$$Ri = Rs \times log_2(M) x\, fec$$

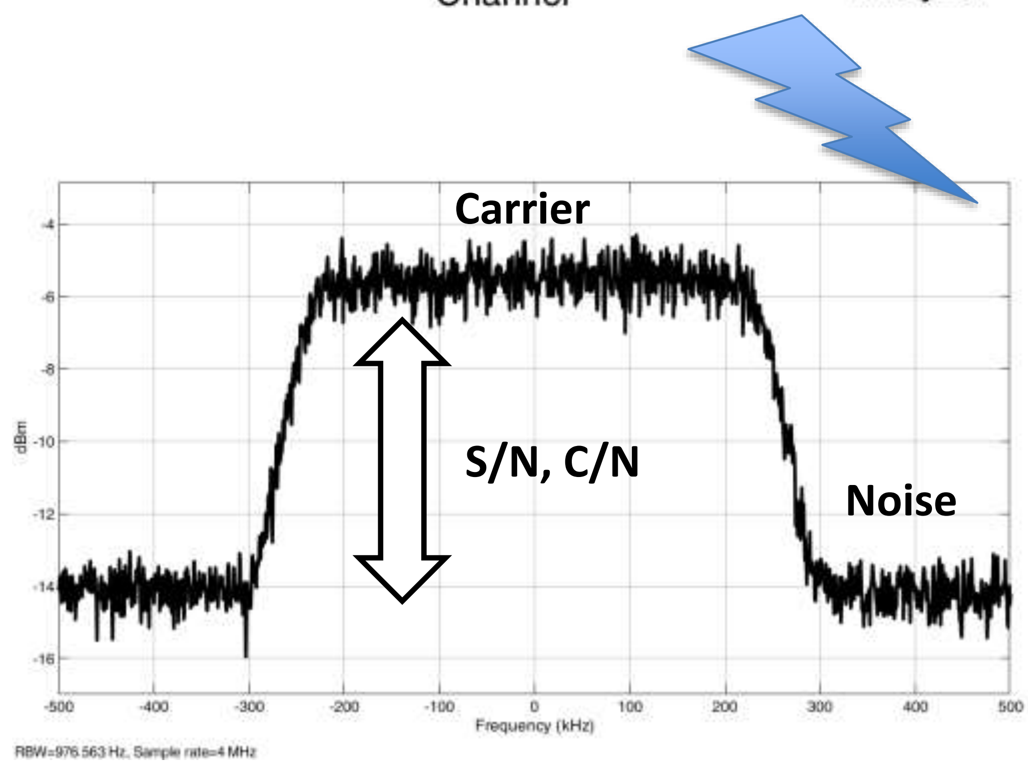
BW: $bandwidth$

Rs: $symbol\ rate$

Ri: $bit\ rate$

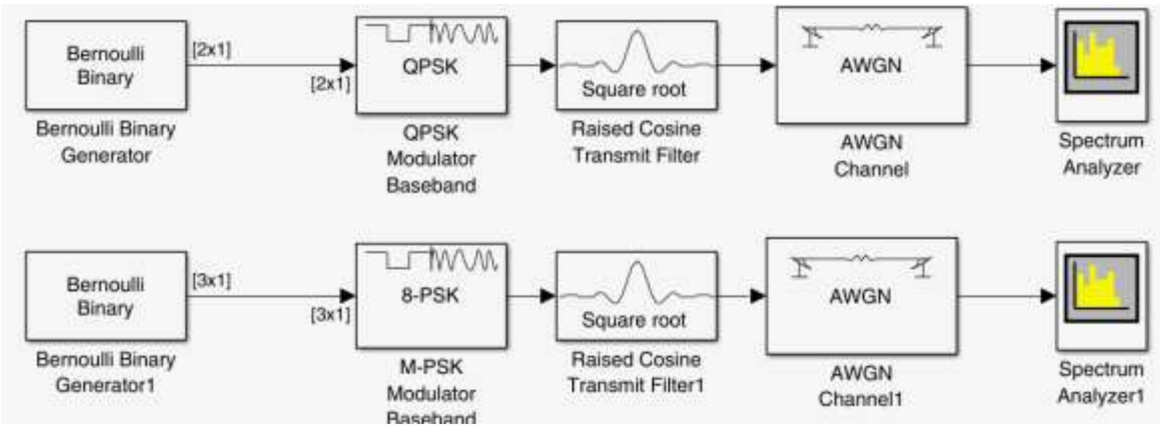
M: $MPSK, 2,4,8$

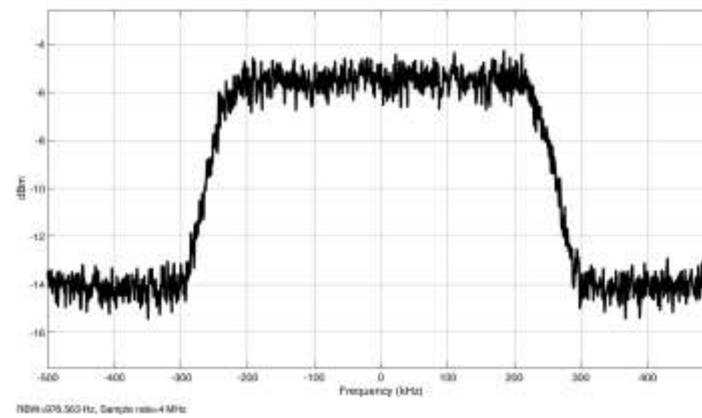
r: $roll\ off\ factor$

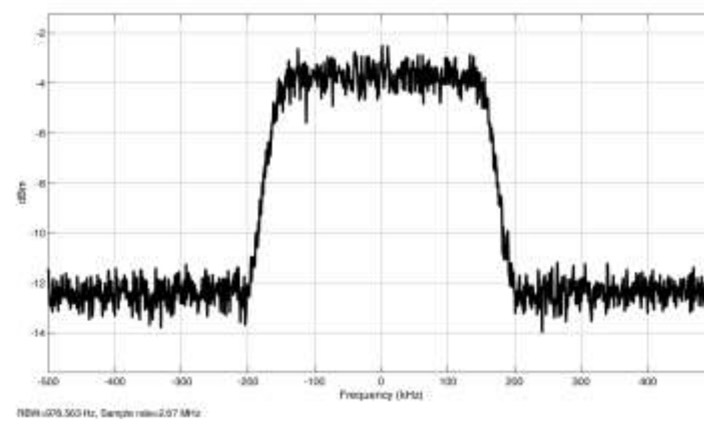


Ri = 1Mbps, Rs=Ri/2=500 Ksps
rolloff = 0.2
BW=Rs . (1+ro)
BW=1.2 x 500 Kaps = 600 Khz

8PSK Bandwidth







QPSK:
Ri = 1Mbps, Rs=Ri/2=500 Ksps
rolloff = 0.2
BW=Rs . (1+ro)
BW=1.2 x 500 Kaps = 600 Khz

8PSK:
Ri=1Mbps, Rs=Ri/3=333 Ksps
BW=1.2 x 333 = 400 Ksps
<u>**8PSK has lower BW**</u>

Satellite Communication
Data Rate - Information Rate

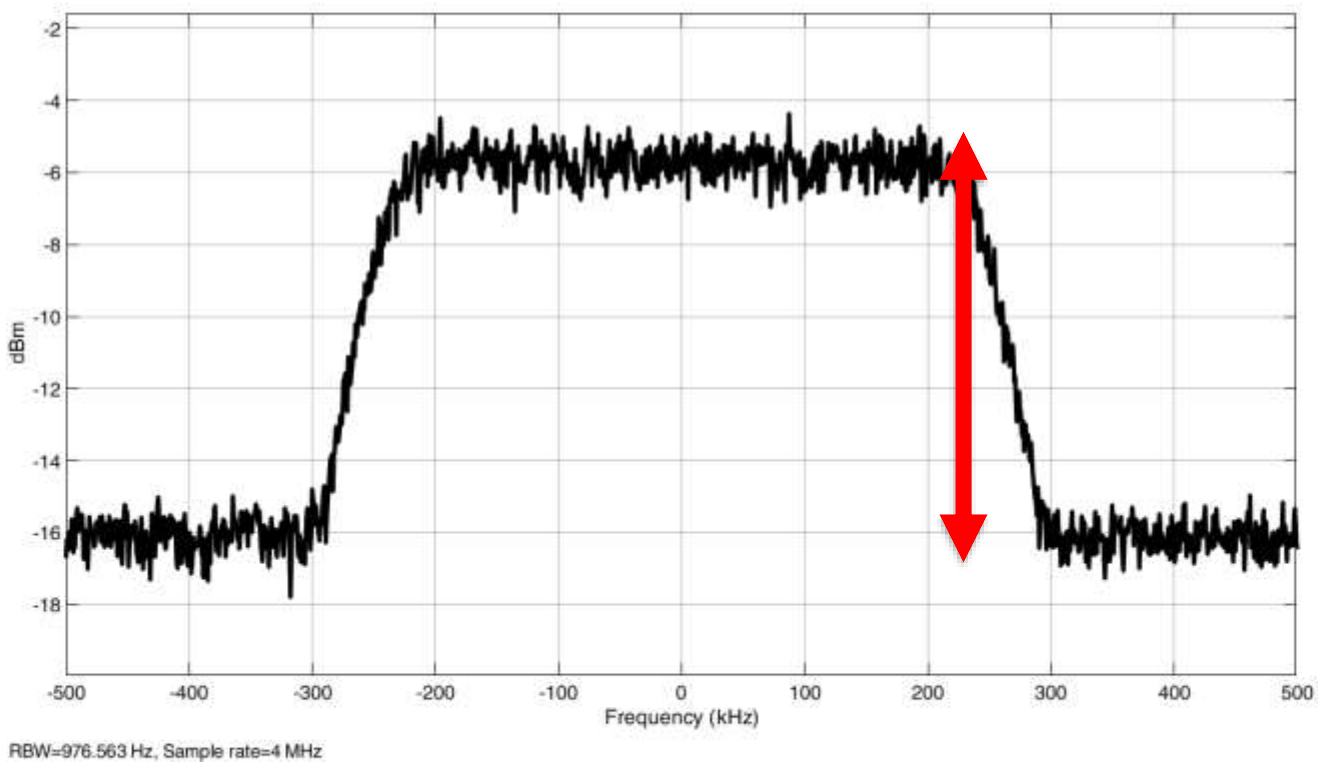
- FEC ratio 5/6 ¾, 1/2 coding adds redundancy bits for error correction. Thus useful information rate reduces

$$BW = (1 + r) \times Rs$$
$$Ri = Rs \times m \times \text{fec}$$
$$BW\text{: } bandwidth$$
$$Rs\text{: } symbol\ rate$$
$$Ri\text{: } info\ bit\ rate$$
$$\mathbf{m}\text{: } \mathbf{1}\ \boldsymbol{bpsk}, \mathbf{2}\ \boldsymbol{qpsk}, \mathbf{3}\ \mathbf{8}\boldsymbol{psk}$$
$$\text{r: } roll\ off\ factor$$

Rs	30.000	ksps
MPSK	3	
fec	3/4	
ro	0,2	
Ri	67.500	kbps
BW	36.000	kHz

Carrier to Noise Ratio

- C/N carrier to noise ratio gives us the level of carrier wrt noise
- example C=-6dBm, N=-16dBm, C/N = -6 – (-16) = 10dB



Power Decibel

- 10log(W)=dBW

- examples:
- 1W= 10log(1W)=0dBW

- dB=10log(P1/P2) power ratio

- -3dB =10log (1/2) means power drops to half
- -6dB means power drops to 1/4

C/N and Eb/No

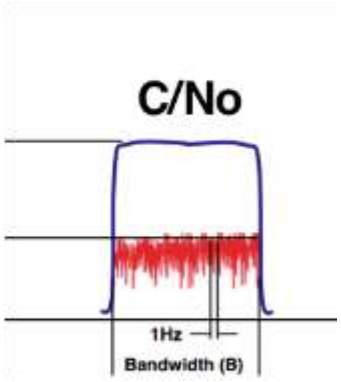
- DVB-S and DVB-S2 uses Eb/No, Es/No instead of C/N for the quality measure of the signal.
- Eb energy per bit, No noise spectral density

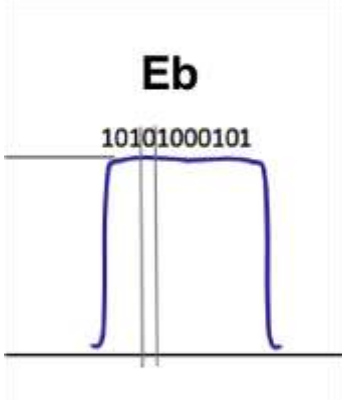
$$\frac{C}{N} = \frac{Eb \times Ri}{No \times Bw}$$

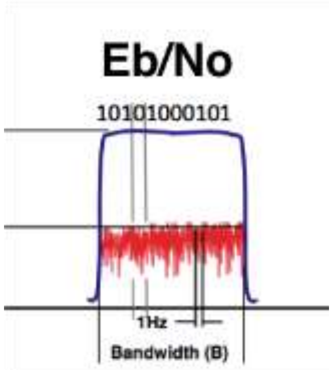
$$\frac{C}{N} = \frac{Eb}{No} \times \frac{Ri}{Bw}$$

$$\frac{C}{N} = \frac{Eb}{No} + 10 \log\left(\frac{Ri}{Bw}\right)$$

$$\boldsymbol{\frac{Eb}{No} = \frac{C}{N} - 10\log\left(\frac{Ri}{Bw}\right)}$$



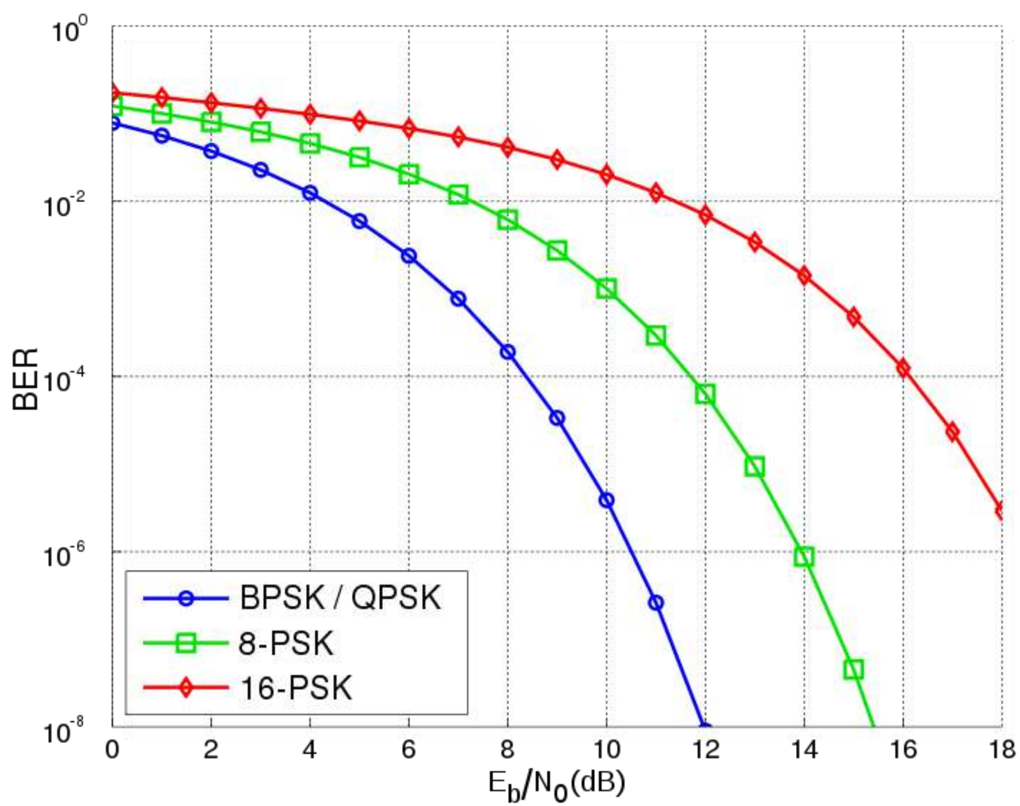




Satellite Communication
BER vs Eb/No

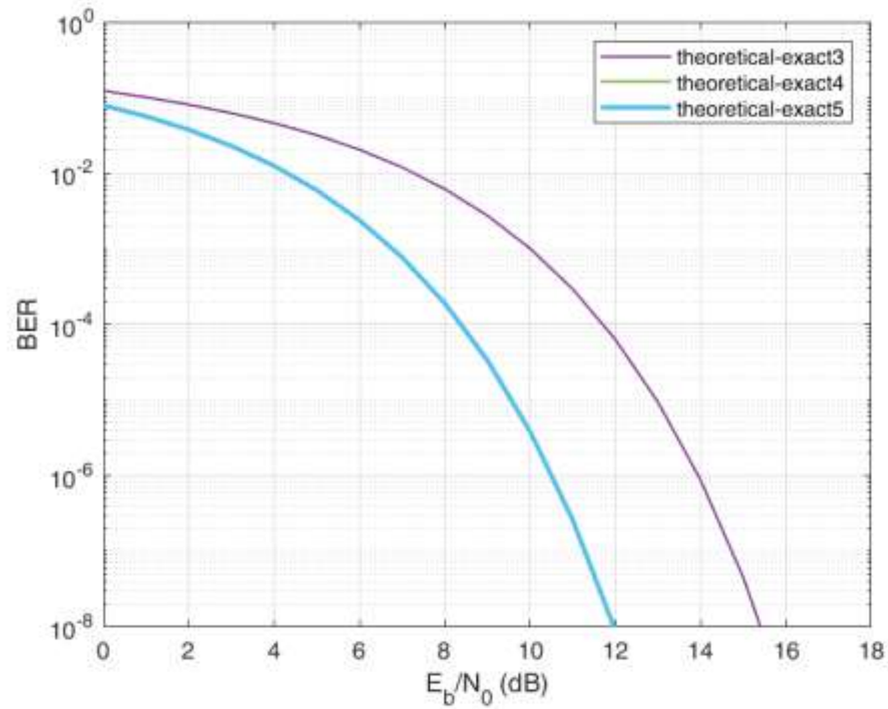
- BPSK and QPSK has the same BER for the same Eb/No, because QPSK is sum of two orthogonal BPSK modulation

$$BER = \frac{1}{2} erfc\left(\sqrt{\frac{E_b}{N_o}}\right)$$



BERTOOL

- run bertool in MATLAB command line
- BPSK and QPSK is the same
- for a given BER , 8PSK requires higher Eb/No



Satellite Communication
DVB-S Eb/No Requirements

- **Quasi Error Free** (QEF) **Packet Error Rate PER=10^-7**
- Eb/No thresholds will be targets at link budget calculations

Inner code rate	Required E_b/N_o for BER = 2×10^{-4} after Viterbi QEF after Reed-Solomon
1/2	4,5
2/3	5,0
3/4	5,5
5/6	6,0
7/8	6,4

DVB-S2 Es/No Requirements

- Spectral efficiency is the ratio of user information bits to total frame length which includes error code bits.
- In DVB/S it was easy to calculate and was directly proportional to FEC and RS ratios. **In DVB-S2, it is given as table due to complexity**
- Eb/No threshold will be used in link budget calculations

$$\frac{E_b}{N_o} = \frac{E_S}{N_o} - 10\log(h_{eff})$$

$$h_{eff} : spectral\ efficiency$$

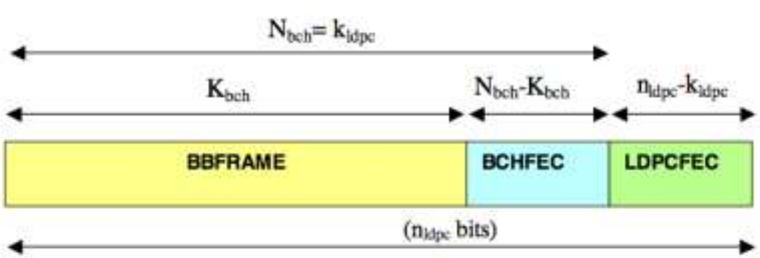


Table 13: E_s/No performance at Quasi Error Free PER = 10^{-7} (AWGN channel)

Mode	Spectral efficiency	Ideal E_s/No (dB) for FECFRAME length = 64 800
QPSK 1/4	0,490243	-2,35
QPSK 1/3	0,656448	-1,24
QPSK 2/5	0,789412	-0,30
QPSK 1/2	0,988858	1,00
QPSK 3/5	1,188304	2,23
QPSK 2/3	1,322253	3,10
QPSK 3/4	1,487473	4,03
QPSK 4/5	1,587196	4,68
QPSK 5/6	1,654663	5,18
QPSK 8/9	1,766451	6,20
QPSK 9/10	1,788612	6,42
8PSK 3/5	1,779991	5,50
8PSK 2/3	1,980636	6,62
8PSK 3/4	2,228124	7,91
8PSK 5/6	2,478562	9,35
8PSK 8/9	2,646012	10,69
8PSK 9/10	2,679207	10,98
16APSK 2/3	2,637201	8,97
16APSK 3/4	2,966728	10,21
16APSK 4/5	3,165623	11,03
16APSK 5/6	3,300184	11,61
16APSK 8/9	3,523143	12,89
16APSK 9/10	3,567342	13,13
32APSK 3/4	3,703295	12,73
32APSK 4/5	3,951571	13,64
32APSK 5/6	4,119540	14,28
32APSK 8/9	4,397854	15,69
32APSK 9/10	4,453027	16,05

NOTE: Given the system spectral efficiency η_{tot} the ratio between the energy per information bit and single sided noise power spectral density $E_b/N_0 = E_s/N_0 - 10\log_{10}(\eta_{tot})$

DVB-S2 Es/No Requirements

8PSK 3/5	1,779991	5,50
8PSK 2/3	1,980636	6,62
8PSK 3/4	2,228124	7,91
8PSK 5/6	2,478562	9,35
8PSK 8/9	2,646012	10,69
8PSK 9/10	2,679207	10,98
16APSK 2/3	2,637201	8,97
16APSK 3/4	2,966728	10,21
16APSK 4/5	3,165623	11,03
16APSK 5/6	3,300184	11,61
16APSK 8/9	3,523143	12,89
16APSK 9/10	3,567342	13,13
32APSK 3/4	3,703295	12,73
32APSK 4/5	3,951571	13,64
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32APSK 8/9	4,397854	15,69
32APSK 9/10	4,453027	16,05

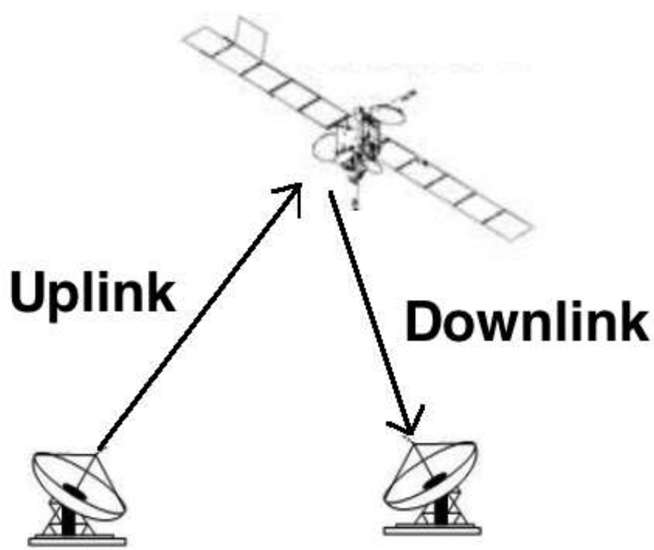
NOTE: Given the system spectral efficiency η_{tot} the ratio between the energy per information bit and single sided noise power spectral density $E_b/N_0 = E_s/N_0 - 10\log_{10}(\eta_{tot})$

Satellite Communication Term Project Ideas

1. DVB-S modulator and demodulator (QPSK 3/4) including line coding chain using Simulink. Use DVB-S2 Link Example
2. HPA Nonlinearity effects (Saleh model) using Simulink with a QPSK modulator. Use RF Satellite Link example.
3. HPA nonlinearity effects using two QPSK carrier.
4. HPA nonlinearity effects using two sinewave carrier.
5. BER vs carrier spacing for two QPSK carrier 4MHz. Use Adjacent and co-channel interference examples
6. BER vs cross-poll interference for two QPSK carriers 4MHz (copol) and 2MHz (x-pol). Use Adjacent and co-channel interference examples
7. Sinusoidal carrier interference. Use pass-band example. Find carrier C/I level to block a 4 MHz QPSK 3/4 carrier (DVB-S Eb/No threshold or BER).
8. QPSK Eb/No vs BER curve using Simulink
9. 8PSK Eb/No vs BER curve using Simulink
10. Calculate a and e for a given 3 or more true anomaly and time measurements for a satellite with i=0
11. TV Broadcasting Survey: Use www.lyngsat.com, import to Excel automatically. Analyze the market. Number of channels per country, per satellite operator. Modulation, FEC, Symbol rate statistics. Etc.
12. GEO Satellite Survey: using geo.txt from www.celestrak.org, import to Excel automatically. Number of GEO satellites, station kept and drift satellites, maximum inclination, eccentiricity. Crowded orbits (moving average), satellites per launch year.

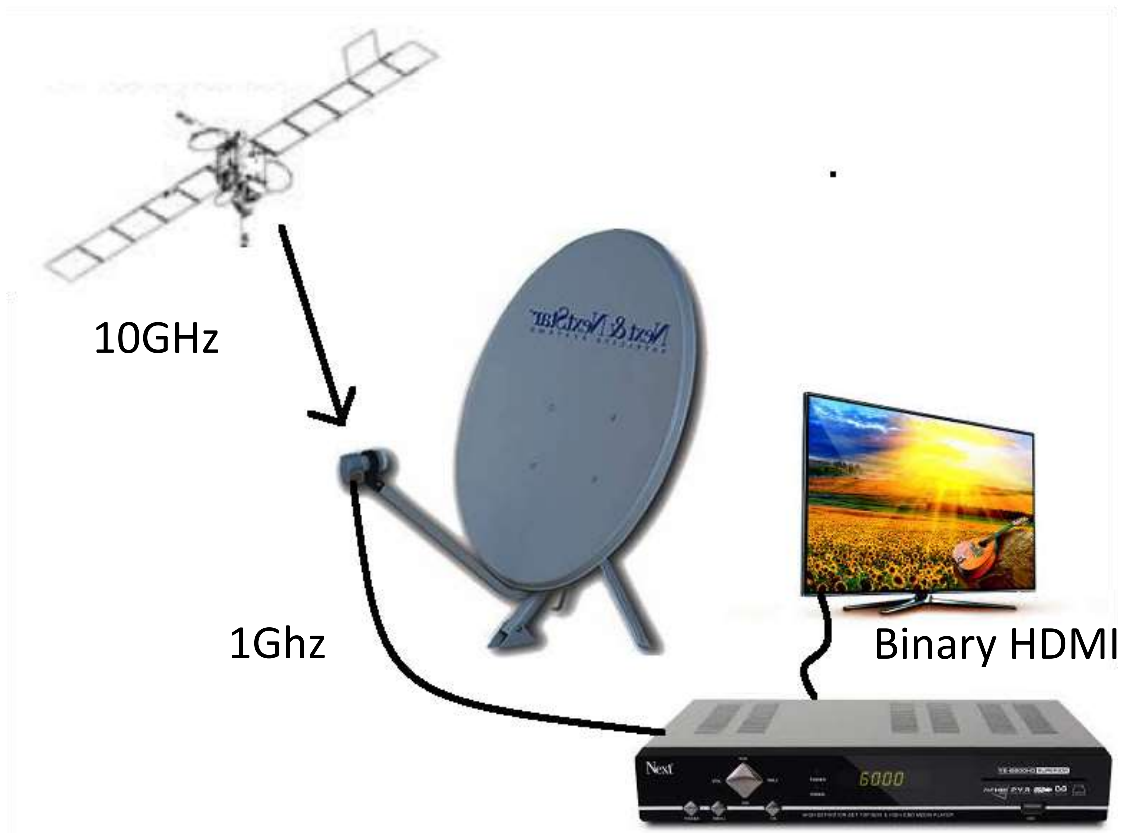
Satellite Communication
Uplink-Downlink

- Communication link between two ground earth station using satellite is divided into two parts: uplink and downlink. Uplink is transmit of signals from ground to satellite and downlink is reception of signals from the satellite.



Satellite Communication Downlink-TV Broadcasting

- TV signals received by an TVRO antenna. **LNB (Low Noie Block Converter)** amplifies and down converts Ku band 10.700-12.750GHz frequency to 1-2GHz band**. Set Top Box (STB)** demodulates and decodes DVB-S or DVB-S2. HDMI, SCART or RGB cable connected to TV.



Satellite Communication Downlink- LNB

- Low Noise Block-converter (LNB) is located at the focal point of the reflector. LNB converts received electromagnetic signals to electronic signals and route the satellite receiver through coaxial cable. LNB is powered from coaxial cable. 13V for Vertical, 18V for Horizontal polarization
- Universal LNB's are widely used in TV broadcasting, covering 10.700 to 12.750 GHZ
- LNB converts 10.700-11.700 (low band) to 950-1950 using **9750MHz LO** and converts 11.700-12.750 (high band) to 1100-2150MHz using 10600MHz LO.
- 10600 LO selection is performed using 22KHz tone from the receiver

Satellite Communication Downlink- Coaxial Cables

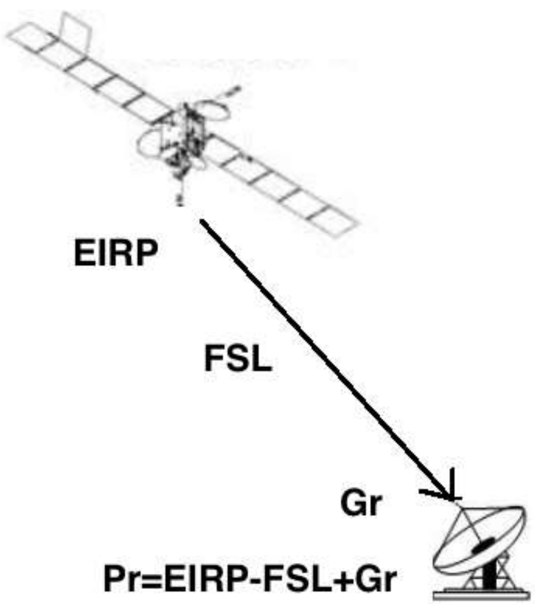
- Coaxial cables are categorized by their inner copper and outer diameters.
- High diameter cables has lower losses due to lower resistances
- RG6 is suitable for TV reception
- RG59 is for cable TV network up to 860MHz

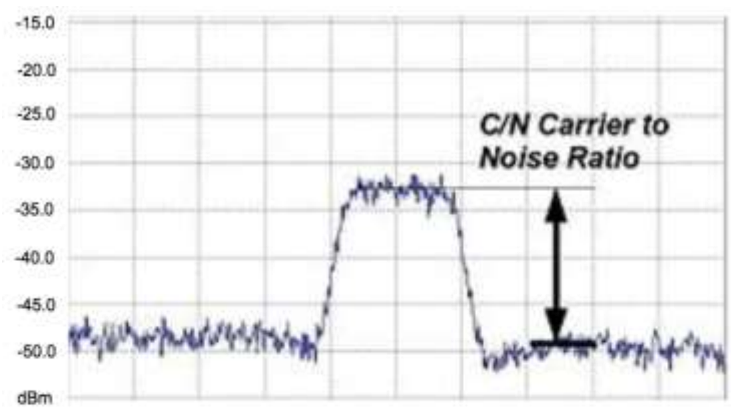
Cable Loss dB/100m													
MHz	5	10	50	100	200	400	550	870	1250	1750	2150	2500	3000
RG59	2,9	3,5	5,4	8,2	12,6	16,0	19,4	24,7	30,6	37,7	40,8	44,7	48,6
RG6	2,2	2,5	5,2	6,6	9,6	13,1	15,5	19,7	24,3	29,3	32,9	35,9	39,8
RG11	1,3	2,0	3,8	5,0	6,9	8,1	9,7	12,6	16,7	20,3	22,9	25,1	28,1

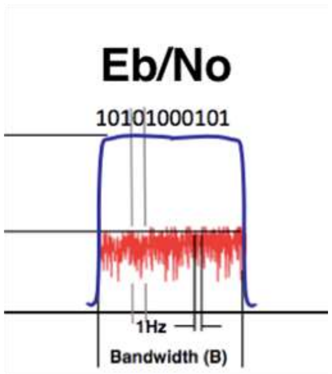
Cable	Rin (mm)	Rout (mm)
RG59	0,81	3,55
RG6	1,02	4,57
RG11	1,63	7,10

Satellite Communication
Downlink Link Budget

- What is the target of downlink Link Budget calculations:
- **given a satellite**, how can I select my receiver parameters such as Antenna, LNB, to receive the TV or Data signal from the satellite
  1. **First calculate C/N**
  2. **Calculate Eb/No, Es/No**
  3. **Check if within requirements**







Satellite Communication Downlink- C/N

- C/N=(Power Received)/(Noise).
- Now we can calculate C/N for downlink

C/N: Carrier to Noise
EIRP: Satellite EIRP
Gr: Receive Antenna Gain
Lfs: Free Space Loss
k: Boltzman constant
T: Receive System Temperature
B: Bandwidth of the carrier

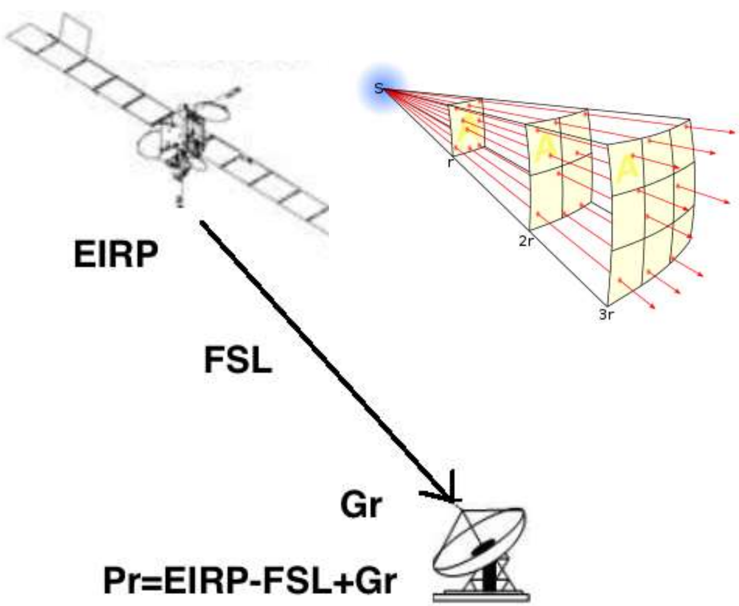
$$\frac{C}{N} = \frac{\left(\frac{EIRP.Gr}{FSL}\right)}{kTB}$$

$$\boxed{\boldsymbol{\frac{C}{N} = EIRP - FSL + Gr - 10\log(T.B) + 228.6\ dB}}$$

DOWNLINK EIRP

$$\frac{C}{N} = \boldsymbol{EIRP} - FSL + Gr - 10\log(T.B) + 228.6\ dB$$

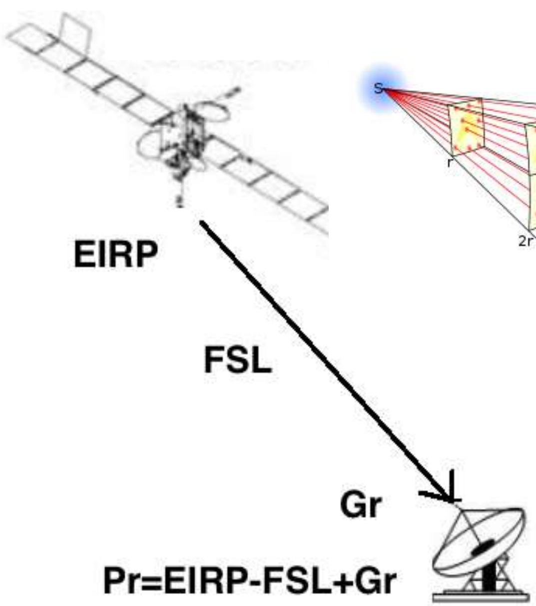
- Satellite EIRP is given by the satellite operator

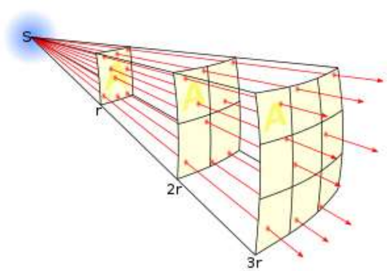


Free Space Loss

- Free space loss (FSL) is the attenuation of the signal due to distance from satellite to the ground earth station. FSL is inversely proportional to square of the distance.

$$\frac{C}{N} = EIRP - \boldsymbol{FSL} + Gr - 10\log(T.B) + 228.6\ dB$$





$$FSL = \left(\frac{4\pi S}{\lambda}\right)^2$$
$$\boldsymbol{FSL = 20\log(F.S) + 92.5\ dB}$$
F: $frequency\ GHz$
S: $Distance\ to\ satelite\ km$

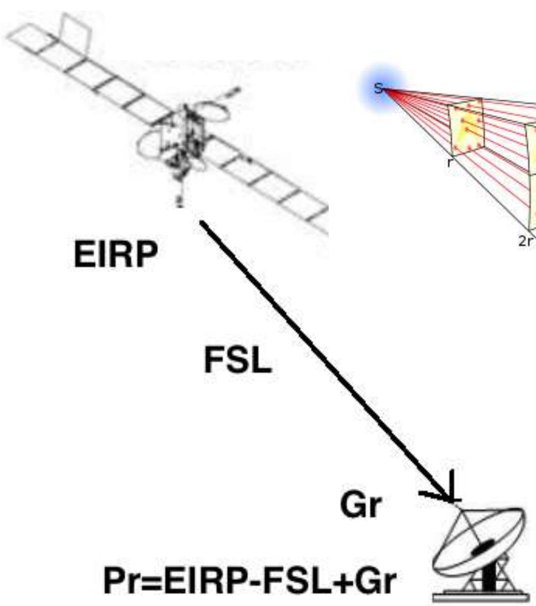
example: F=12Ghz, S=37570km
FSL=20log(12x37570)+92.5=205.6 dB

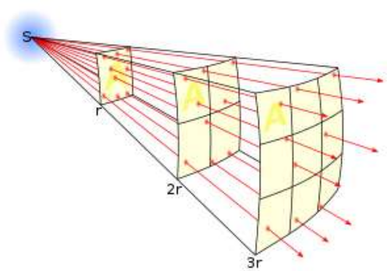
Distance to Satellite
Slant Range

- Distance to satellite defines the Free Space Loss

$$\frac{C}{N} = EIRP - \boldsymbol{FSL} + Gr - 10\log(T.B) + 228.6\ dB$$

$$FSL = 20\log(F.S) + 92.5\ dB$$
$$F: frequency\ GHz$$
$$S: Distance\ to\ satelite\ km$$
$$S = \sqrt{Rs^2 + Re^2 + 2RsRecos(g)}$$
$$\cos(g) = \cos(\Delta long)\cos(lat)$$
$$Rs = 42164km, Re = 6378km$$
$$\Delta long = longsat - longrx$$



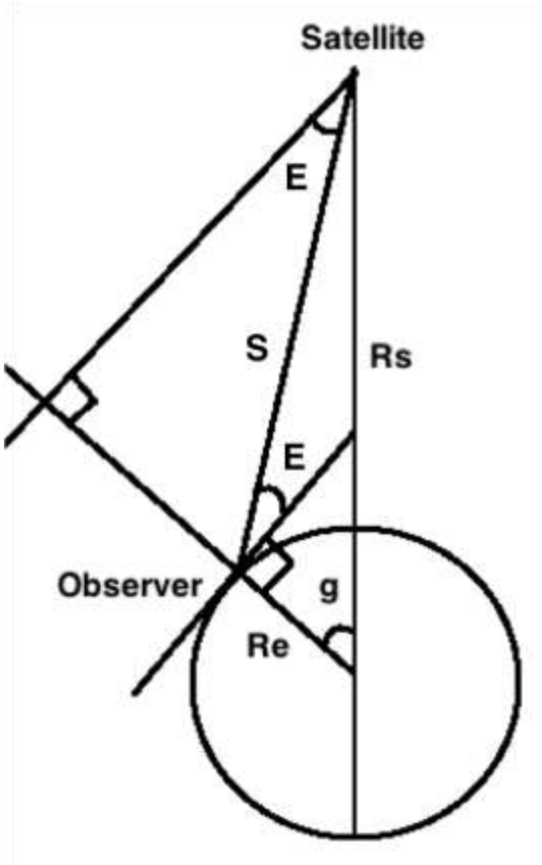


example: Turksat 3A longsat=42
Ankara longrx=33, latrx=40

S=37570 km to the satellite

Satellite Slant Range

- Slant range is distance to satellite from the observer.
- This distance will be important to calculate the signal loss from/to the satellite.



$$S = \sqrt{R_S^2 + R_e^2 - 2 R_S R_e \cos(g)}$$

$$\cos(g) = \cos(\Delta Long)\cos(Lat_{Observer})$$

Antenna Gain

- Antenna Gain formula is given as
- $G = 20\log(F.D) + 10\log(\eta) + 20.4\ dB$
- we can simplify by taking antenna efficiency **n=0.65**

$$\frac{C}{N} = EIRP - \boldsymbol{FSL} + Gr - 10\log(T.B) + 228.6\ dB$$

$$\boxed{G = 20\log(F.D) + 18.53\ \ dB}$$

Downlink- Noise

- All electronic systems have noise.
- System noise power spectral density can be modeled No=k*T
- T represents the thermo- dynamic temperature of a resistance which delivers the same available noise power as the source under consideration.
- T is not real physical temperature, it is an equivalent temperature.
- Communication signals will have a limited bandwidth. Thus the noise we are interested is the noise within this bandwidth N=k*T*B
- Sometimes, systems noise temperature of electronic devices (LNB etc) is given as Noise Figure.

$$N_o = kxT, \mathrm{N{=}kxTxB}$$

$$k = 1.379x10^{-23} = -228.6 \text{ dBW/Hz (Boltzman's constant)}$$

$$T : \text{System Noise Temperature (Kelvin)}$$

$$T = 290(10^{\frac{NF}{10}} - 1), NF = 10\log(1+\frac{T}{290})$$

Satellite Communication Downlink- Noise

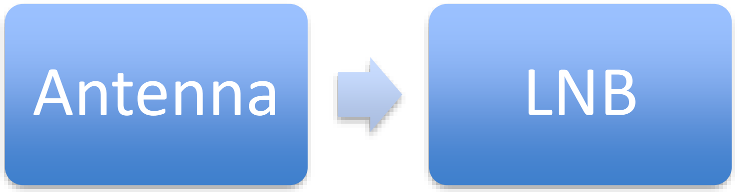
- Typical downlink system has antenna and LNB
- Assuming that there is negligible loss between antenna and LNB (feed loss). 1dB attenuation causes 7K system noise temperature increase

- System noise temperature at the input of the receiver can be calculated as:

$$\boldsymbol{Ts = Ta + Tlnb}$$

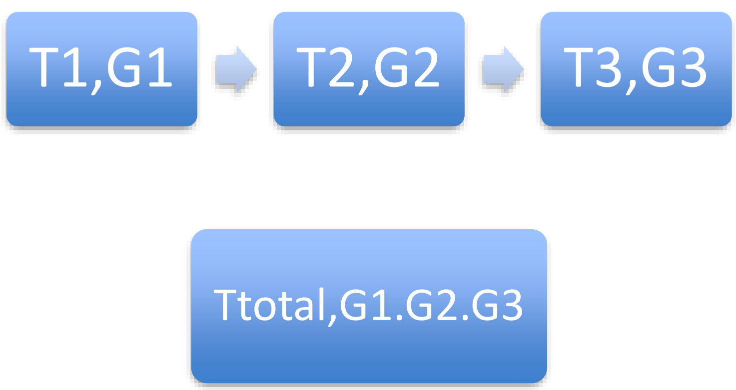
$$\boldsymbol{Tlnb = 290\left(10^{\frac{NF}{10}} - 1\right)}$$

- Example: Ta=50K, LNB NF=0.8
- Ts=109K



Satellite Communication Downlink- Noise

- Total system noise temperature of cascaded electronic systems can be calculated.
- Attenuator effective noise temperature is T(L-1).
- Cascaded amplifiers after a system can be calculated. Notice that temperature of the first system is more effective compare to remaining systems.
- **Addition of active device to the system always increase the total system noise temperature**.



$$T_{eff} = (L - 1)T_L$$

$$T_{Total} = T_1 + \frac{T_2}{G_1} + \frac{T_3}{G_1 G_2}$$

$$T_{Total} G_1 G_2 G_3 = T_1 G_1 G_2 G_3 + T_2 G_2 G_3 + T_3 G_3$$

Downlink- DVB-S2 Link Budget

- EIRP=52dBW, F=11GHz, DVB-S2 8PSK 3/4, symbol rate=30000, rolloff=1.35 receive antenna=60cm, Required Es/No for DVB-S2 8PSK 3/4 is **7.91 dB** and **Seff=2.228124**

11054 V tp 10 West 52	DVB-S2 8PSK 30000 3/4	TRT	*TRT*
		10600	TRT Çocuk
		10601	TRT 1
		10602	TRT Haber
		10603	TRT Spor
		10604	TRT Belgesel
		10605	TRT World
		10606	TRT Türk
		10608	TRT Müzik
		10609	TRT Kurdî

DVB-S2 Es/No Requirements

8PSK 3/5	1,779991	5,50
8PSK 2/3	1,980636	6,62
8PSK 3/4	2,228124	7,91
8PSK 5/6	2,478562	9,35
8PSK 8/9	2,646012	10,69
8PSK 9/10	2,679207	10,98
16APSK 2/3	2,637201	8,97
16APSK 3/4	2,966728	10,21
16APSK 4/5	3,165623	11,03
16APSK 5/6	3,300184	11,61
16APSK 8/9	3,523143	12,89
16APSK 9/10	3,567342	13,13
32APSK 3/4	3,703295	12,73
32APSK 4/5	3,951571	13,64
32APSK 5/6	4,119540	14,28
32APSK 8/9	4,397854	15,69
32APSK 9/10	4,453027	16,05

NOTE: Given the system spectral efficiency η_{tot} the ratio between the energy per information bit and single sided noise power spectral density $E_b/N_0 = E_s/N_0 - 10\log_{10}(\eta_{tot})$

Downlink- DVB-S2 Link Budget

- EIRP=52dBW at Ankara F=11GHz, DVB-S2 8PSK 3/4, symbol rate=30000, rolloff=0.35 receive antenna=60cm,
- Required Es/No for **DVB-S2 8PSK 3/4 is 7.91** dB and **Seff=2.228124**
- Calculate C/N, Ri, BW, Eb/No, Es/No and link margin

$$\frac{\mathbf{C}}{\mathbf{N}} = \mathbf{EIRP - FSL + Gr - 10\log(Ts.BW) + 228.6\ dB}$$

$\mathbf{S = 37570}$ km for Ankara

$\mathbf{FSL = 20}\ \boldsymbol{log}(\boldsymbol{F.S}) + \mathbf{92.5}\ \boldsymbol{dB} = 204.8\ \mathrm{dB}$

$\mathbf{Gr = 20\log(F.D) + 18.53} = 35\ \mathrm{dBi}$

$$\mathbf{Ta = 50K, NF = 1, Tlnb = 290\left(10^{\frac{NF}{10}} - 1\right) = 75K\ Ts = Ta + Tlnb = 125K}$$

$\mathbf{BW = (1 + ro).Rs} = 40.5\ \mathrm{Mhz}, 10\log(\mathrm{Ts.Bw}) = 97\mathrm{dB}$

$$\frac{\mathbf{C}}{\mathbf{N}} = \mathbf{52\ - 204.8 + 35\ - 97 + 228.6 =\ 13.8\ dB}$$

$\mathbf{Rinfo = Rs.Seff} = 66.843\ \mathrm{Mbps}$ $\quad \frac{\mathbf{Eb}}{\mathbf{No}} = \frac{\mathbf{C}}{\mathbf{N}} - \mathbf{10\log}\left(\frac{\mathbf{Ri}}{\boldsymbol{BW}}\right) = \mathbf{11.47dB}$

$$\frac{\mathbf{Es}}{\mathbf{No}} = \frac{\mathbf{Eb}}{\mathbf{No}} + \mathbf{10\log(Seff) = 14.95dB}, \mathrm{Required}\frac{\mathrm{Es}}{\mathrm{No}} = \mathbf{7.91dB}, \mathrm{Margin} = +7\mathrm{dB}$$

Downlink- DVB-S2 Link Budget

- EIRP=52dBW at Ankara F=11GHz, DVB-S2 8PSK 3/4, symbol rate=30000, rolloff=1.35 receive antenna=60cm,
- Required Es/No for DVB-S2 8PSK 3/4 is 7.91 dB and Seff=2.228124
- Calculate C/N, Eb/No, Es/No and link margin

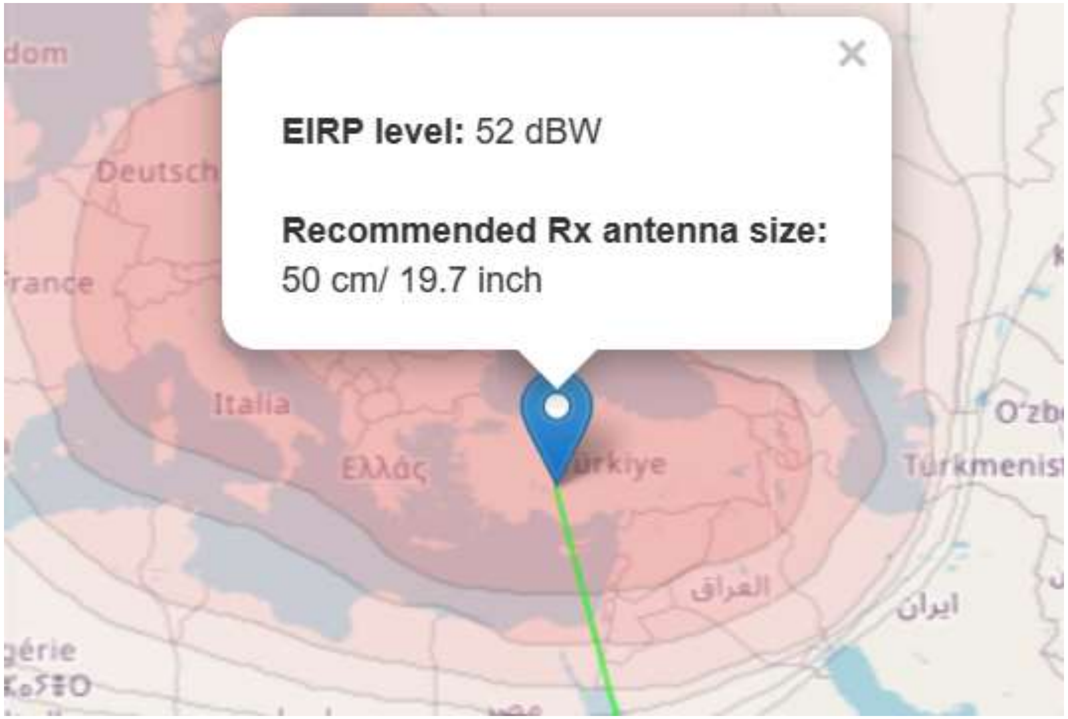
- There are limited options to increase the margin in downlink because satellite parameters are fixed
- Antenna Diameter: **Gr=20log(F.D)+18.53 dB**, increasing diameter from 0,6m to 1,2m gives us +6dB additional margin
- LNB NF: NF figure of professional LNB's may be 0.7dB-0.8dB there are OEM LNB's with 0.1dB NF but not correct. Decreasing NF from 1dB to 0.8dB gives us +0.6dB not much
- **So antenna diameter is the most critical parameter for a good reception**
- **Also cable losses after LNB to the receiver has to be kept minimum**

Satellite Communication
Downlink- C/N

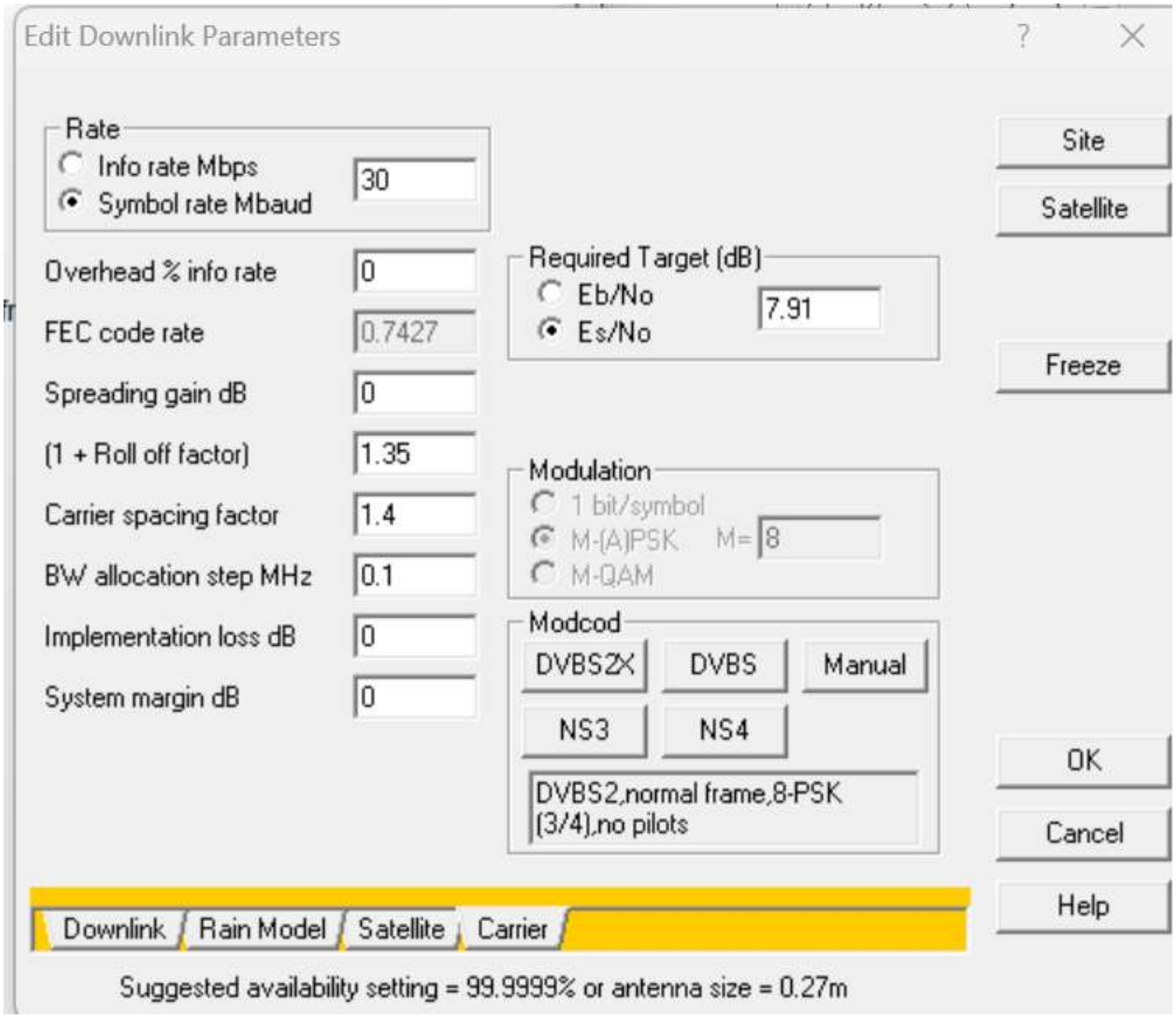
- It is interesting to see that there are only three parameters to change C/N for TV reception for a user:
  1. **Increase the antenna diameter**
  2. Use LNB with low NF
  3. Use good quality and short length RG6 coaxial cables. RG59 cables are for cable TV networks at frequencies below 860MHz

Downlink- DVB-S2 Link Budget

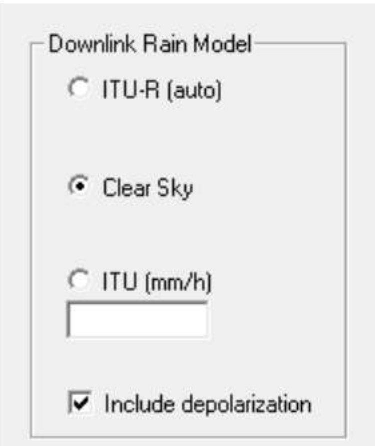
https://www.satbeams.com/footprints

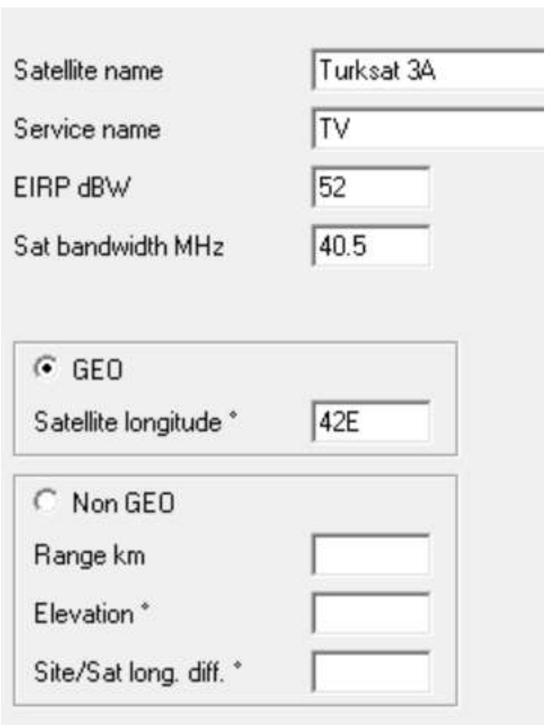


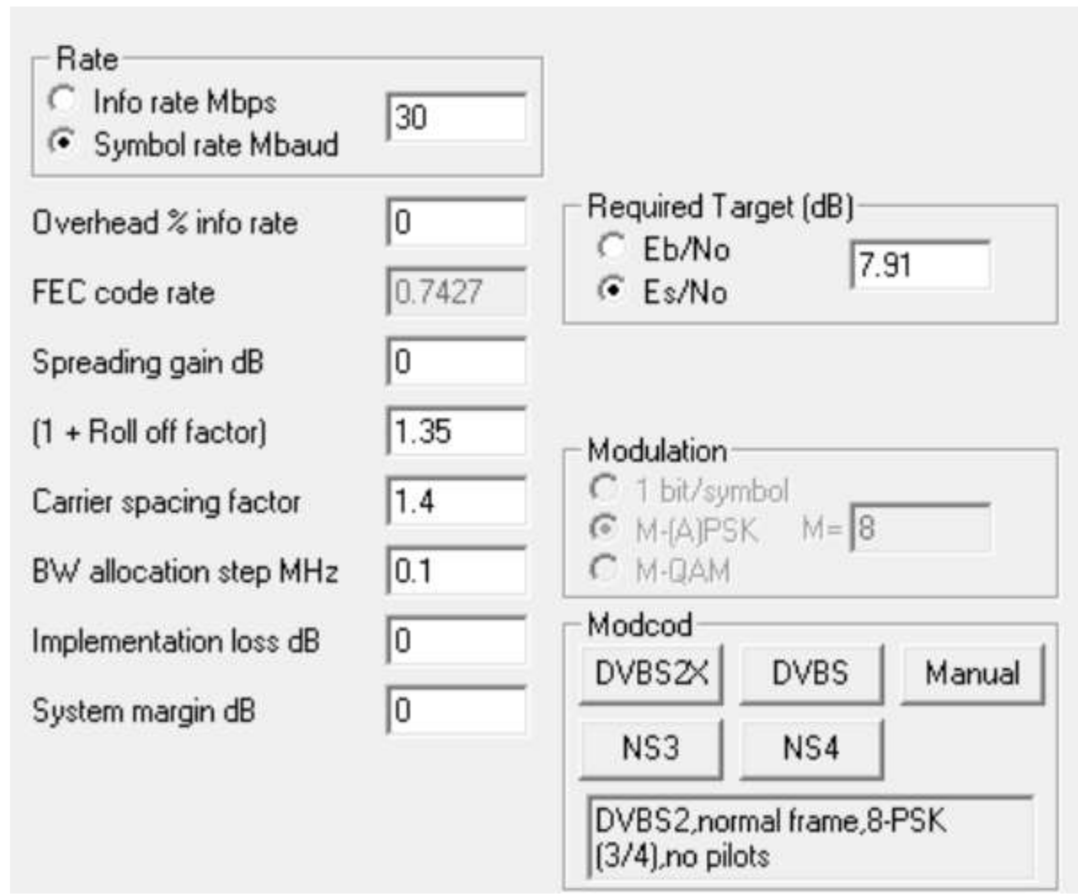
Downlink- DVB-S2 Link Budget



Downlink- DVB-S2 Link Budget







Downlink- DVB-S2 Link Budget

Downlink Budget

Produced using Satmaster Pro

Sunday 28 January 2024

Service Name	TV	
Downlink earth station	Ankara	
Satellite name	Turksat 3A	
Modcod	DVBS2,normal frame,8-PSK (3/4),no pilots	
Link Input Parameters	**Value**	**Units**
Site latitude	40N	degrees
Site longitude	33E	degrees
Site altitude	1.084	km
Frequency	11	GHz
Polarization	vertical	
Rain model	Clear sky	
R0.01%	0	mm/h
Availability (average year)	N/A	%
Antenna aperture	0.6	metres
Antenna efficiency or gain (+ or - prefix)	65	% or dBi
Coupling loss	0	dB
Antenna mispoint loss	0	dB
Other path losses	0	dB
LNB noise figure or temp (+ prefix)	1	dB or K
Antenna noise	50.00	K
LNB gain	60	dB
LNB load impedance	50	Ohms
C/ACI	300	dB
C/ASI	300	dB
C/XPI	300	dB
C/IM	300	dB

Downlink- DVB-S2 Link Budget

Satellite Input Parameters	Value	Units
EIRP (saturation)	52	dBW
Bandwidth	40.5	MHz
Longitude	42E	degrees

Carrier/Link Input Parameters	Value	Units
Modulation	8-PSK	
Required Es/No	7.91	dB
Symbol rate	30	Mbaud
Information rate overhead	0	%
FEC code rate	0.7427	
Spreading gain	0	dB
(1 + Roll off factor)	1.35	
Carrier spacing factor	1.4	
Bandwidth allocation step size	0.1	MHz
Implementation loss	0	dB
System margin	0	dB

General Calculations	Value	Units
Elevation	42.80	degrees
True azimuth	166.16	degrees
Compass bearing	159.92	degrees
Path distance to satellite	37570.96	km
XPD during rain	0.00	dB
Propagation time delay	0.125323	seconds
Antenna gain	34.93	dBi
Carrier EIRP density (satellite)	-22.77	dBW/Hz
Carrier EIRP density (flange)	-192.68	dBW/Hz
Availability (average year)	N/A	%
Link downtime (average year)	N/A	hours
Availability (worst month)	N/A	%
Link downtime (worst month)	N/A	hours

Downlink- DVB-S2 Link Budget

Downlink Calculation	**Clear**	**Rain**	**Units**
Satellite EIRP per carrier	52.00	52.00	dBW
Antenna mispoint	0.00	0.00	dB
Free space loss	204.77	204.77	dB
Atmospheric absorption (Ag(1%) cap)	0.07	0.07	dB
Tropospheric scintillation	0.00	0.00	dB
Cloud attenuation (Ac(1%) cap)	0.00	0.00	dB
Rain attenuation	0.00	0.00	dB
Total attenuation (gas-rain-cloud-scintillation)	0.07	0.07	dB
Other path losses	0.00	0.00	dB
Noise increase due to precipitation	0.00	0.00	dB
Downlink degradation (DND)	0.00	0.00	dB
Total system noise	127.79	127.78	K
Figure of merit (G/T)	13.86	13.86	dB/K
Power flux density	-110.49	-110.49	dBW/m2
Carrier power at LNB output	-57.85	-57.85	dBW
Carrier power at LNB output	-27.85	-27.85	dBm
Carrier level at LNB output (50 Ohm)	79.14	79.14	dBuV
Carrier level at LNB output (50 Ohm)	19.14	19.14	dBmV
C/No (thermal)	89.62	89.62	dB-Hz
C/N (thermal)	14.85	14.85	dB
C/ACI	300.00	300.00	dB
C/ASI	300.00	300.00	dB
C/XPI	300.00	300.00	dB
C/IM	300.00	300.00	dB
C/I (total)	293.98	293.98	dB
C/(N+I)	14.85	14.85	dB
Implementation loss	0.00	0.00	dB
System margin	0.00	0.00	dB
Net Es/(No+Io)	14.85	14.85	dB
Required Es/(No+Io)	7.91	7.91	dB
Excess margin	**6.94**	**6.94**	**dB**

Downlink- DVB-S2 Link Budget

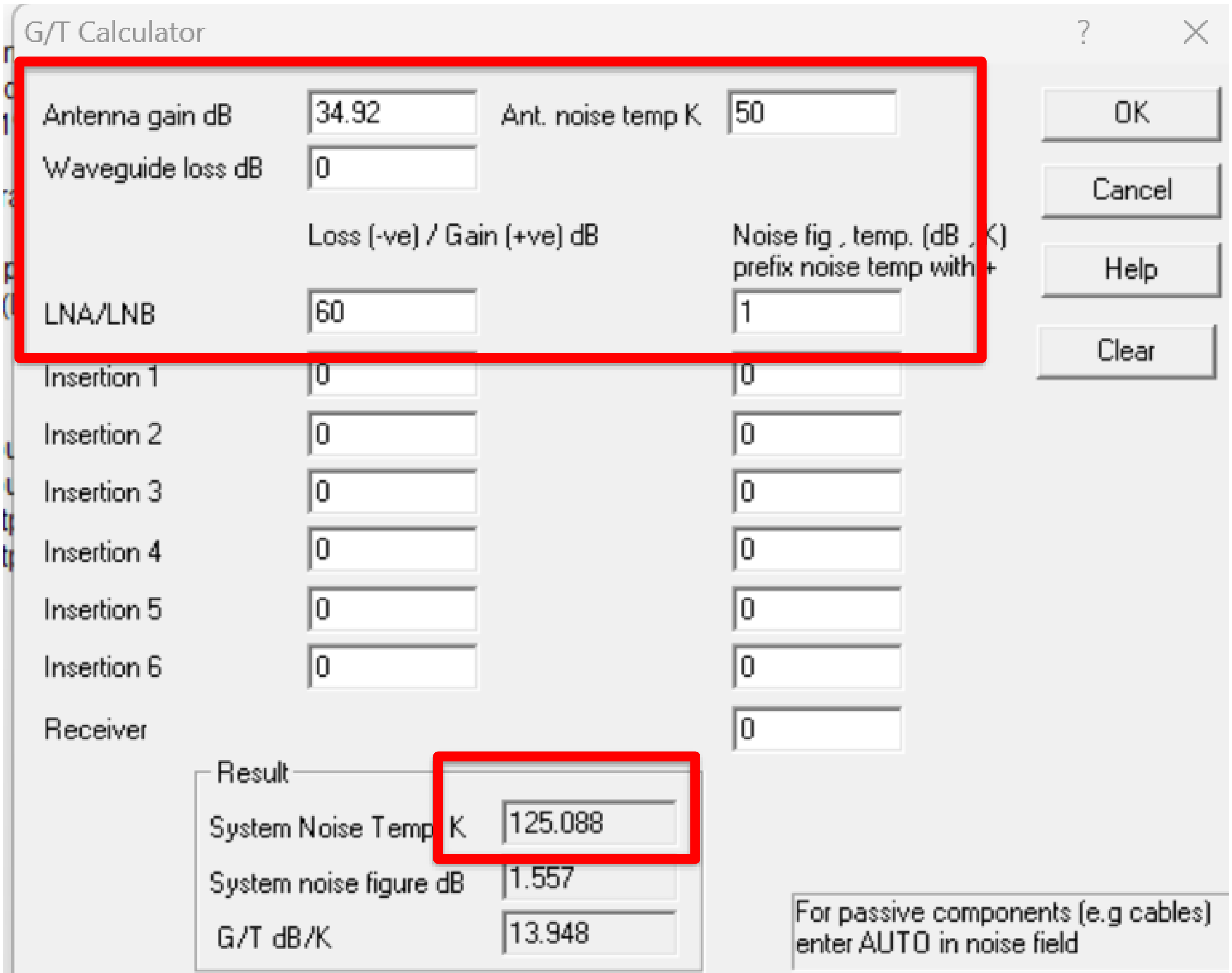
Space Segment Utilization	Value	Units
Information rate	66.8430	Mbps
Information rate (inc overhead)	66.8430	Mbps
Coded bitrate	90.0000	Mbps
Symbol rate	30.0000	MBaud
Noise Bandwidth	74.77	dB-Hz
Occupied bandwidth	40.5000	MHz
Allocated bandwidth	42.0000	MHz

Satmaster Comparison

- We have the same results for downlink budget
- **Total System Noise is calculated as 127.79K while we calculated 125.09K**
- When we use G/T calculation menu we Satmaster calculates the same value 125.09
- It seems that Satmaster putting some losses in system noise calculation
- not a big problem SO we double checked our calculations with an industrial commercial tool and our calculations are OK

- Satmaster Demo does not allow to save but still you can use for calculations

Downlink- DVB-S2 Link Budget



Satellite Communication
Downlink- Antenna Size

Some satellite operators provide antenna size with 6-7 dB margin for rain attenuation and cable losses etc. It is given that 60cm should enough for 52dBW EIRP

EIRP-Antenna Diameter

EIRP	LNB NF (dB)	
	0.6 - 0.7	0.8 - 1.0
55 dBW	50 cm	50 cm
54 dBW	50 cm	55 cm
53 dBW	55 cm	60 cm
52 dBW	60 cm	60 cm

Adaptive Coding and Modulation

- For the same parameters lets change from 8PSK 3/4 to 3/5
- Seff=1.779991, required Es/No=5.50

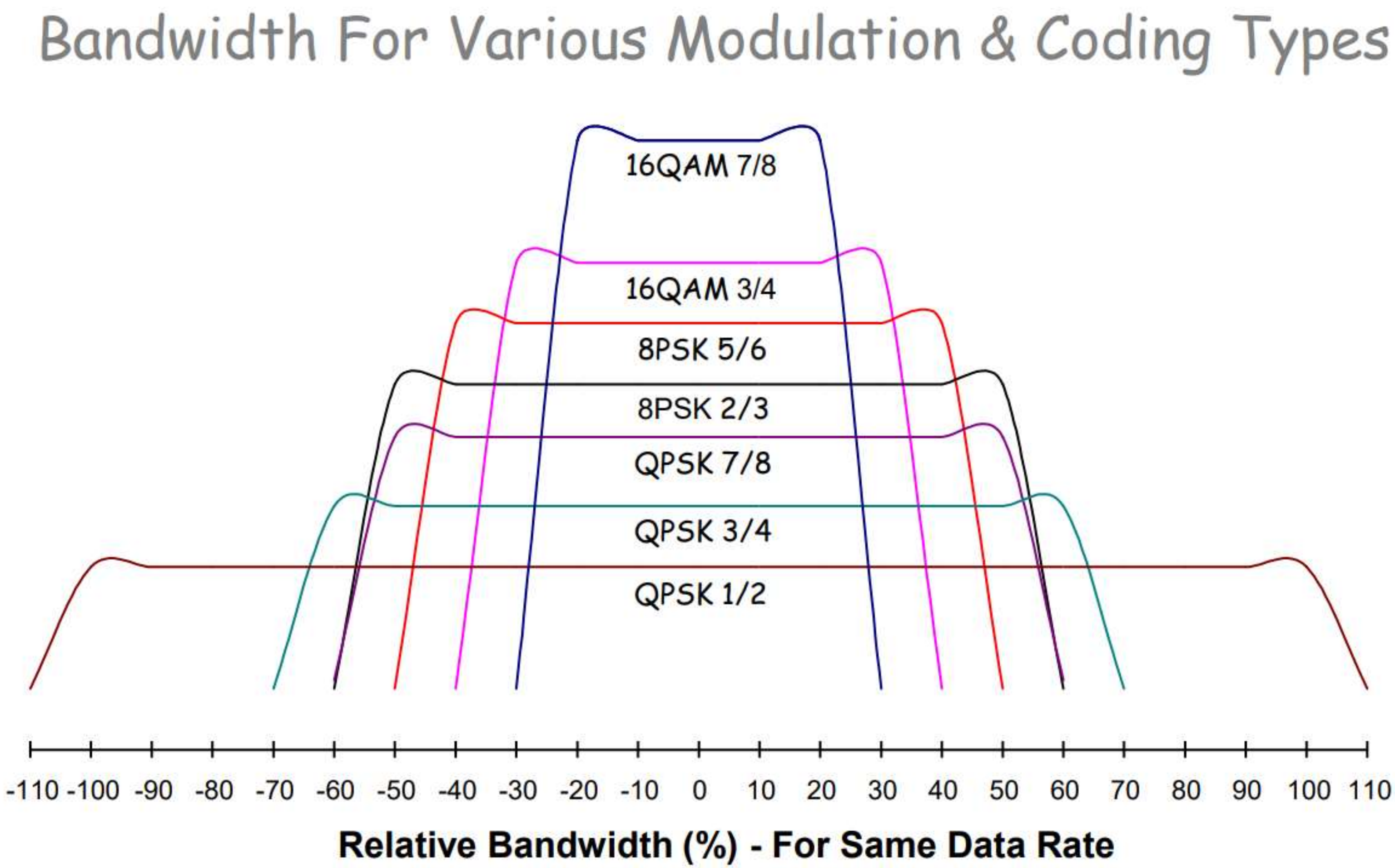
8PSK 3/5	1,779991	5,50
8PSK 2/3	1,980636	6,62
8PSK 3/4	2,228124	7,91

- Ri=66.843Mbps for 8PSK 3/4, Margin=7.04dB
- Ri= 53.399Mbps for **8PSK 3/5 Margin=9.45 dB**

- We increased the margin by +2.4dB **sacrifying lost information rate**

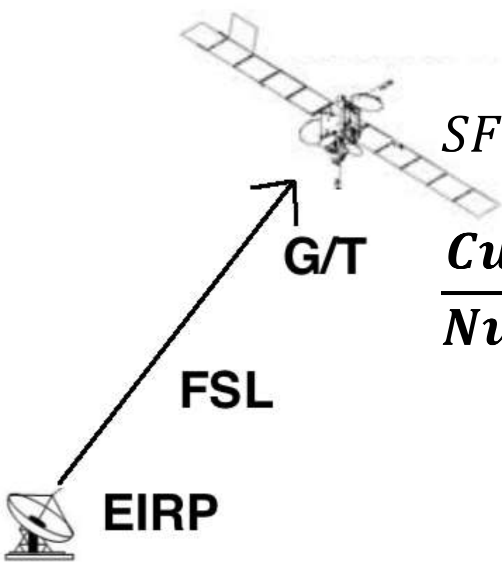
- Can't we do it automatically ? Yes, **Adaptive Coding and Modulation (ACM)** can do it and it is an important advantage of DVB-S2. ACM changes MODCOD (modulation and Coding) in **in case of rain automatically** by sacrifying information rate but link stays UP

Adaptive Coding and Modulation



Satellite Communication
Uplink Link Budget

- Objective of the uplink link budget is to have enough input power flux density to the **satellite receiver thresholds take it -90 dBW/m2 for calculations**
- G/T is given for the satellite operator
- Also C/N of uplink must be high enough to have overall C/N high (uplink + downlink)



$$SFD = EIRPu - 10\log(4\pi S^2)$$

$$\boldsymbol{\frac{Cup}{Nup} = EIRPup - FSL + G/Tsat - 10\log(B) + 228.6\ dB}$$

Satellite Communication
Uplink-Example

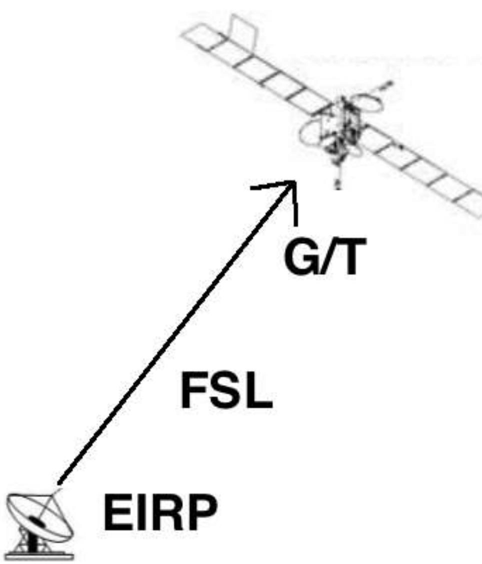
- 200W, 3.7m transmit antenna, 14GHz uplink frequency, **satellite G/T=10,** B=40.5Mhz,
- Calculate uplink C/N and check **if SFD is enough for required SFD=-90 dBW/m2**

$$\boldsymbol{Gtx = 20\log(F.D) + 18.53\ dB = 52.82\ dBi}$$

$$\boldsymbol{EIRPu = 10\log(P) + Gtx = 75.83\ dBW}$$

$$S = 37570\ km, \boldsymbol{FSL = 20\log(F.S) + 92.5 = 206.9dB}$$

$$\boldsymbol{SFD = EIRPu - 10\log\left(4\pi S^2\right) = EIRPu - 20\log(S) - 71}$$



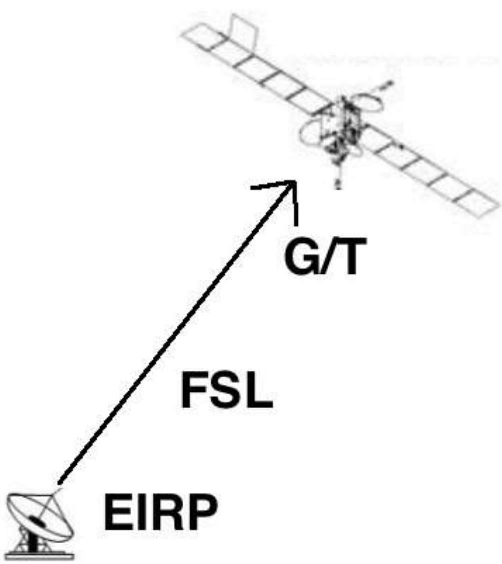
$$= -86.66\ dBW/m2$$ (S in km)

$$\boldsymbol{SFD\ margin = 3.34dB}$$

Satellite Communication
Uplink-Example

- 200W, 3.7m transmit antenna, 14GHz uplink frequency, **satellite G/T=10,** B=40.5Mhz,
- Calculate uplink C/N and check **if SFD is enough for required SFD=-90 dBW/m2**
- **Because C/Nu is 20-30dB and greater compare to downlink.**
- **C/Ntotal ~ C/Ndownlink**

$$\frac{\boldsymbol{Cu}}{\boldsymbol{Nu}} = \boldsymbol{EIRP} - \boldsymbol{FSL} + \boldsymbol{G/Tsat} - \mathbf{10}\,\mathbf{log}(\boldsymbol{B}) + \mathbf{228.6} = 31.43dB$$

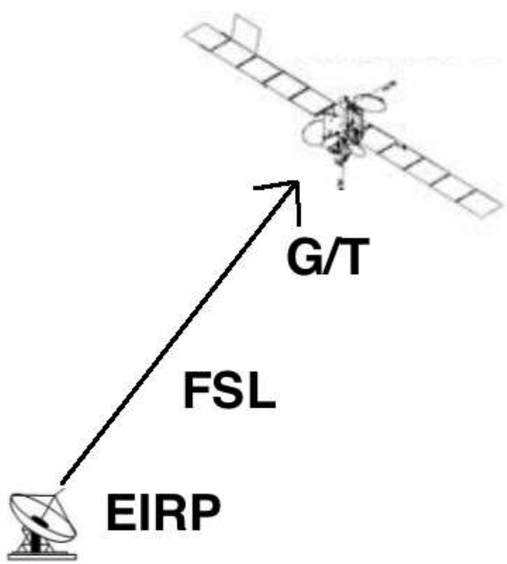


$$\frac{Cdown}{Ndown} = 13.65dB, \frac{Ctotal}{Ntotal} = 13.58dB$$

$$CNtot = -10\log\left(\frac{1}{10^{\frac{CNu}{10}}} + \frac{1}{10^{\frac{CNd}{10}}}\right)$$

Satellite Communication
Uplink-Example

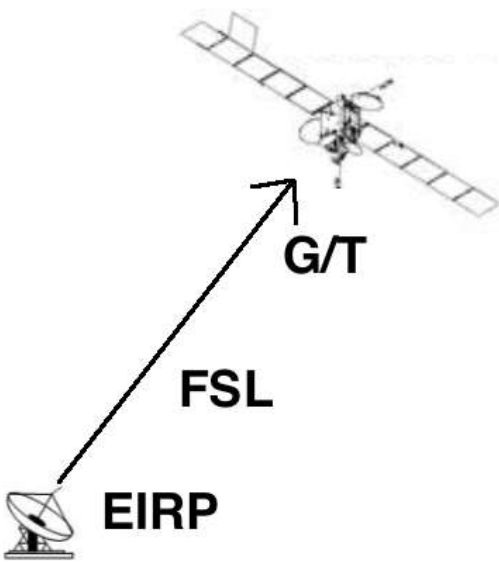
- for the same parameters, we can ask what is the minimum HPA power for SFD requirement ?
- using an excel sheet, we can reduce the HPA power to 94.5W and have 0 margin



Uplink			Calculations		
HPA	94,5	W	Gtx	52,82	dBi
F	14	Ghz	EIRPu	72,57	dBW
longsat	42		S	37570	km
longtx	33		FSL	206,92	dB
lattx	40		SFD	-89,92	dBW/m2
Diameter	3,7	m	SFD margin	0,08	dB
SFDreq	-90	dBW/m2	Bw	40,50	Mhz
G/Tsat	10	dB/K	C/Nup	28,18	dB
			C/Ndown	13,65	dB
			C/Ntotal	13,50	dB

Satellite Communication
Uplink-Summary

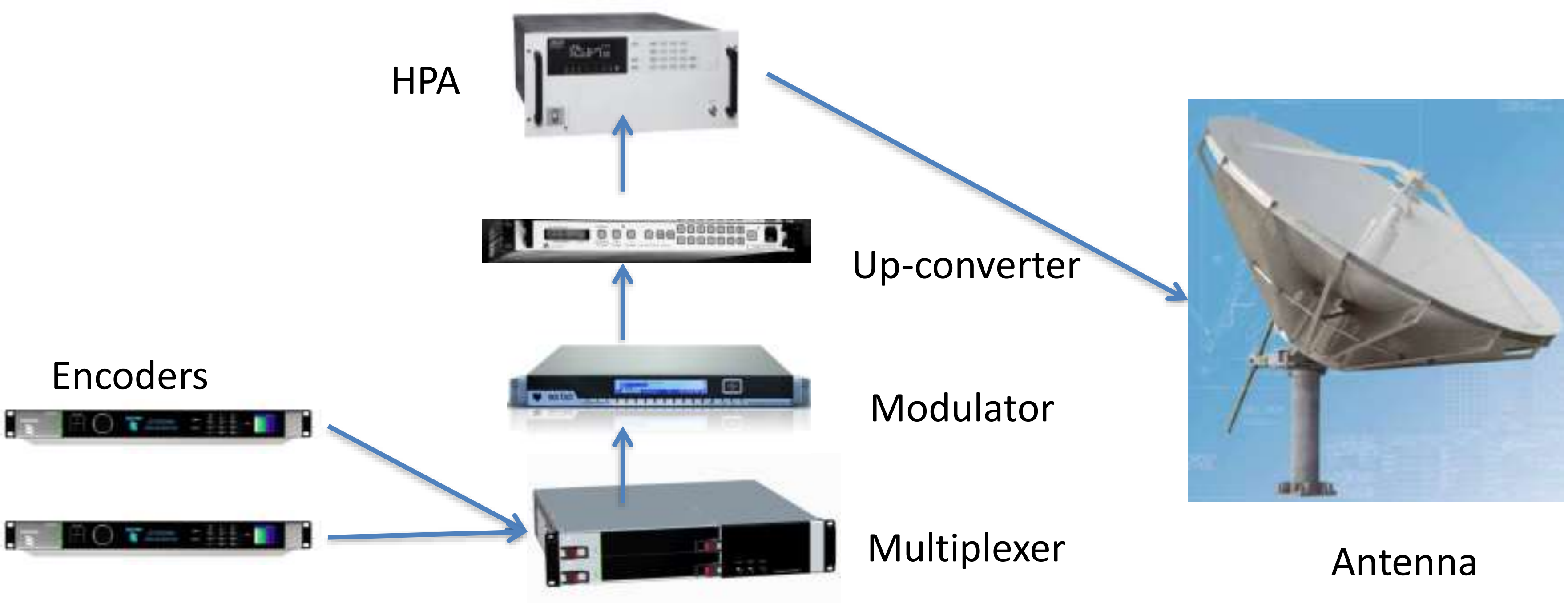
- for the same parameters 2.4m uplink antenna will have a negative margin
- Uplink antenna power and diameter are most important parameters we can change for the link budget.
- Satellite G/T is related to coverage areas. Wide coverage area has low G/T. This situation creates and advantage for spot beams. Spot beams have high G/T and EIRP. This allows small diameter antennas and low power terminals (economy)



- Investment of uplink if expensive. Uplink link budget needs to be coordinated with Satellite operator. Satellite operator has the real parameters of the satellite G/T and saturation flux density, input back-off, output back-off etc.

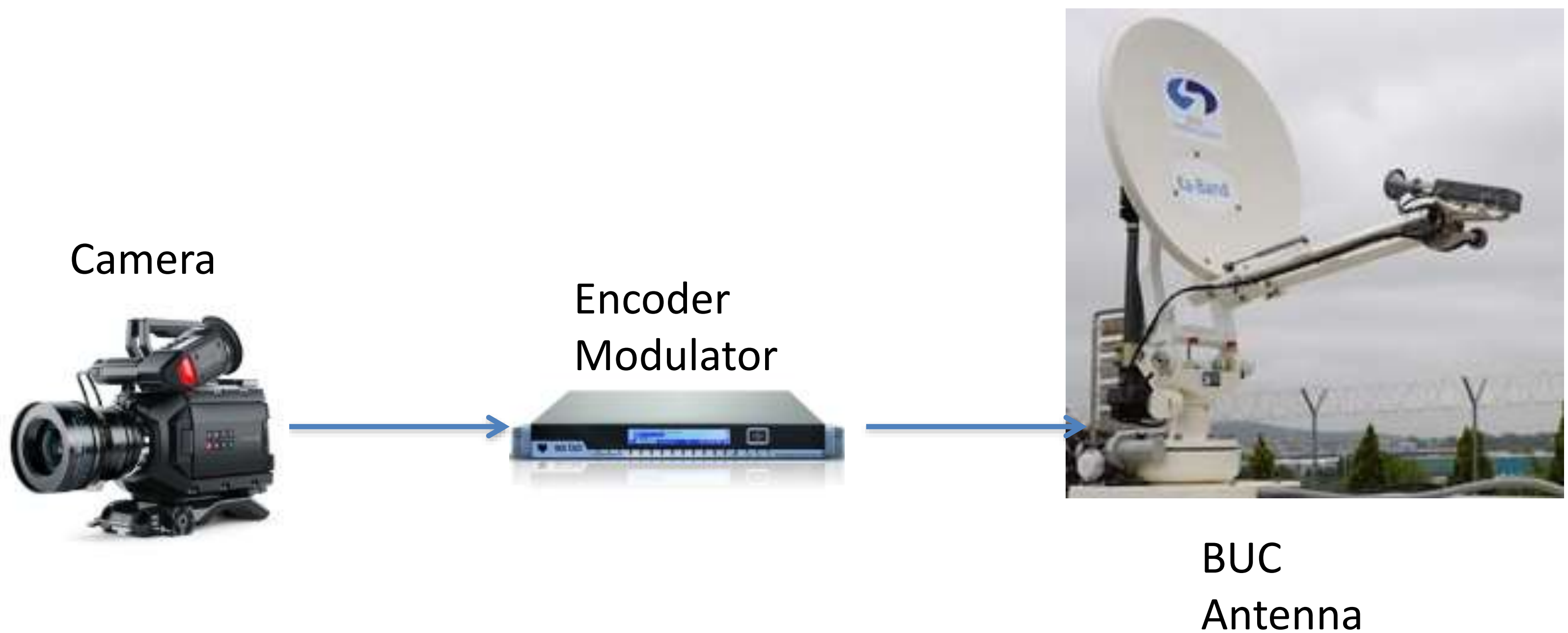
Satellite Communication
Uplink- TV Uplink

- Encoders receive the video signal either directly from a camera or Server (IP) and encodes to MPEG-2 or MPEG-4. Multiplexer receives IP data from many encoders and constructs Transport Stream (TS). Modulator modulates in QPSK, 8PSK. Up-converter input can be IF (70-140MHz) or L Band (1-2GHz) and output is 14GHz (Ku) connected HPA. HPA power amplifies signal and routes the signal to the antenna feeds through waveguides.



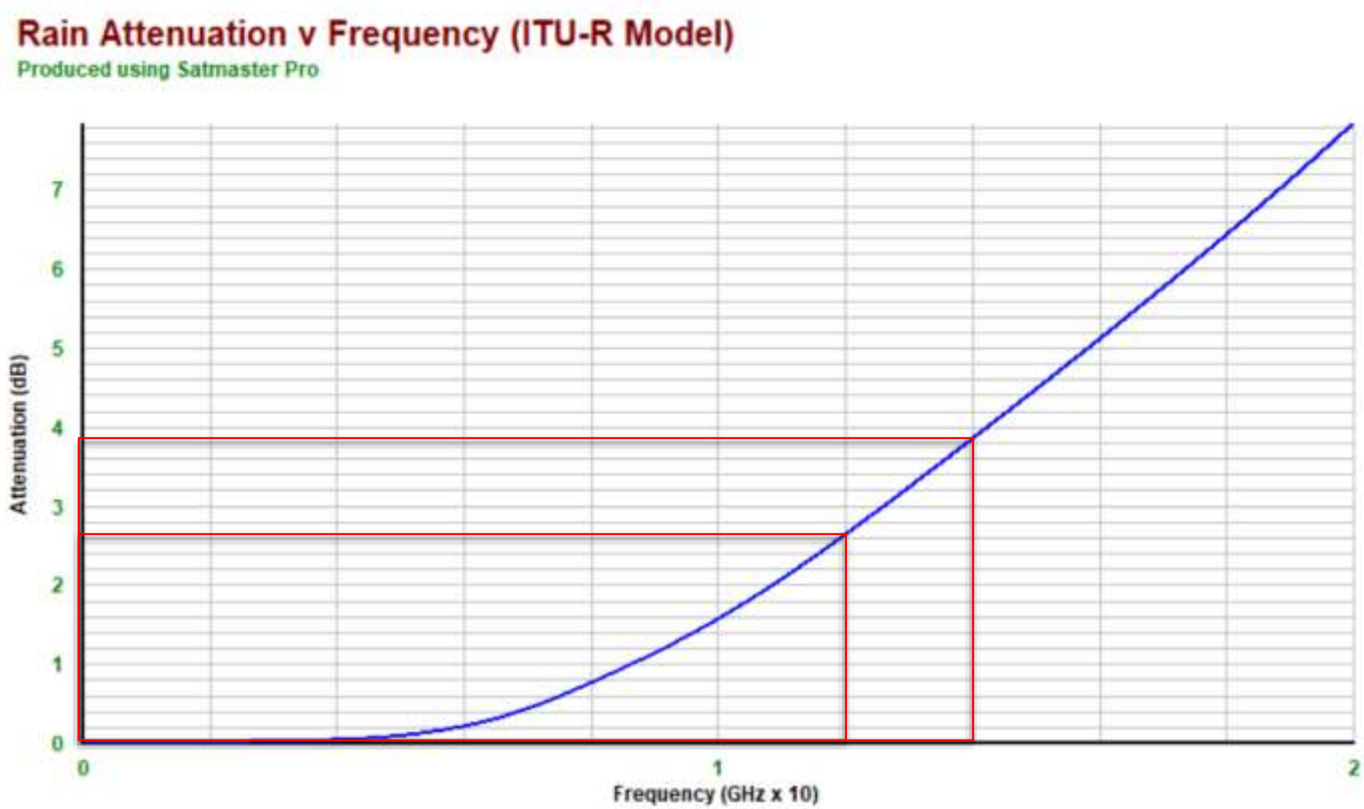
Satellite Communication
Uplink- SNG TV Uplink

- Satellite News Gathering (SNG) has compact uplink with encoder and modulator combined. Block Up-converter replaces up-converter and HPA. Feed is a part of BUC.



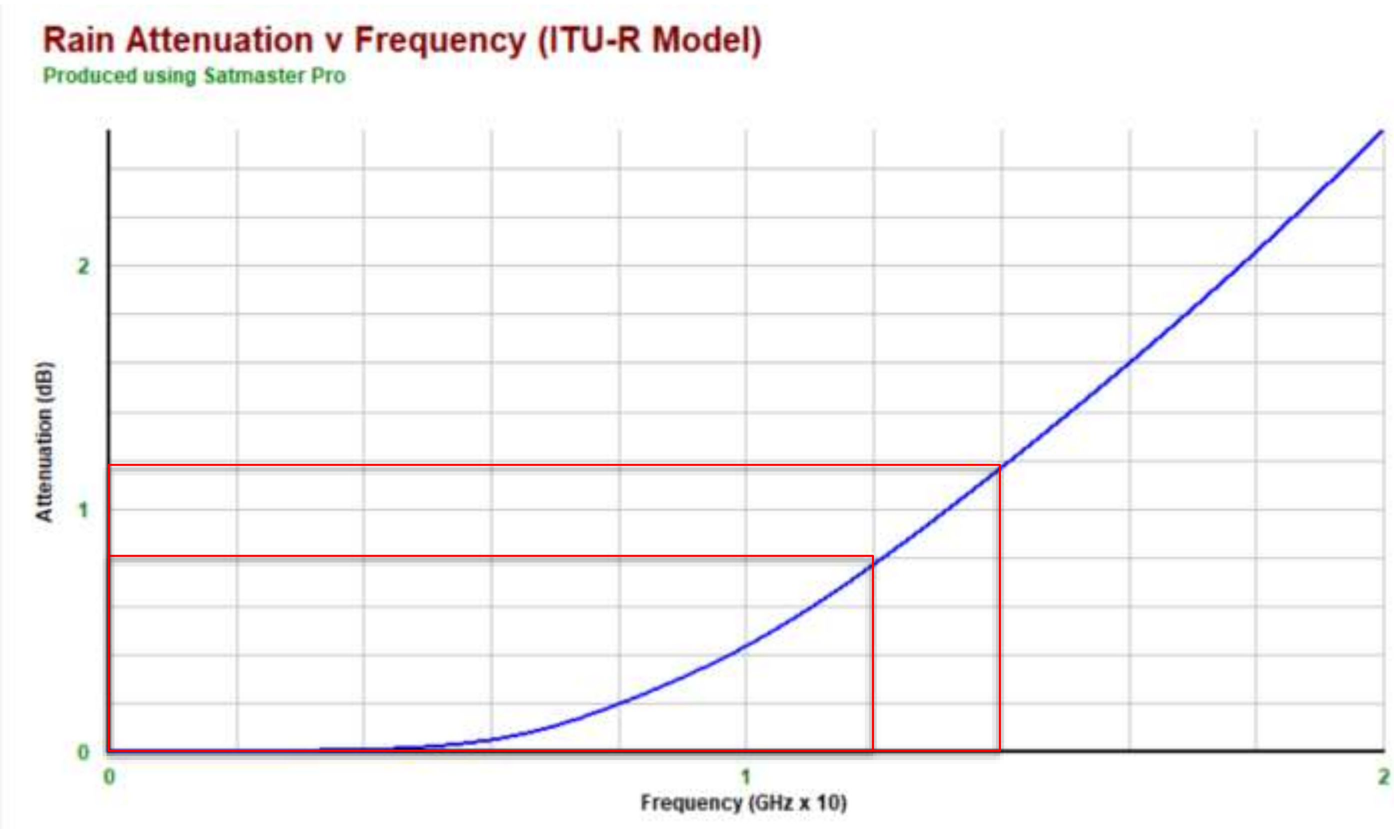
Satellite Communication
Rain Attenuation

- **Turkey is in ITU rain zone “K”.** Specific attenuation is related to frequency and region.
- Rain attenuation for Ankara and Turksat 3A elevation is around 4dB for 14GZ and 3dB for 12 GHz
- **Thus we need 3dB rain margin if we want %99.99 availability** = 52.6 min/year



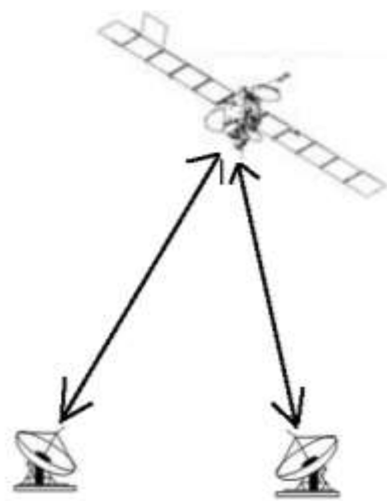
Satellite Communication
Rain Attenuation

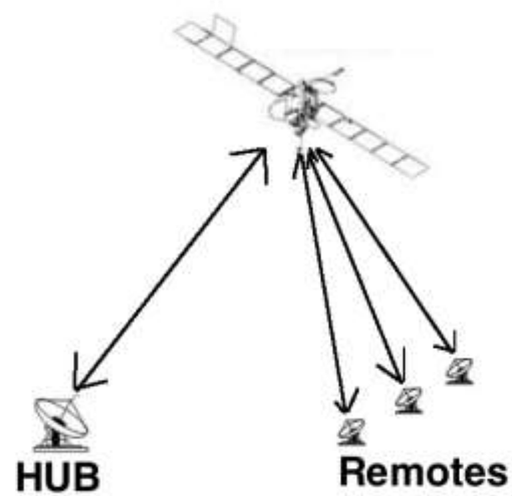
- Rain attenuation drops for %99.90 availability = 8.77 hours/year



Satellite Communication
Data Communication

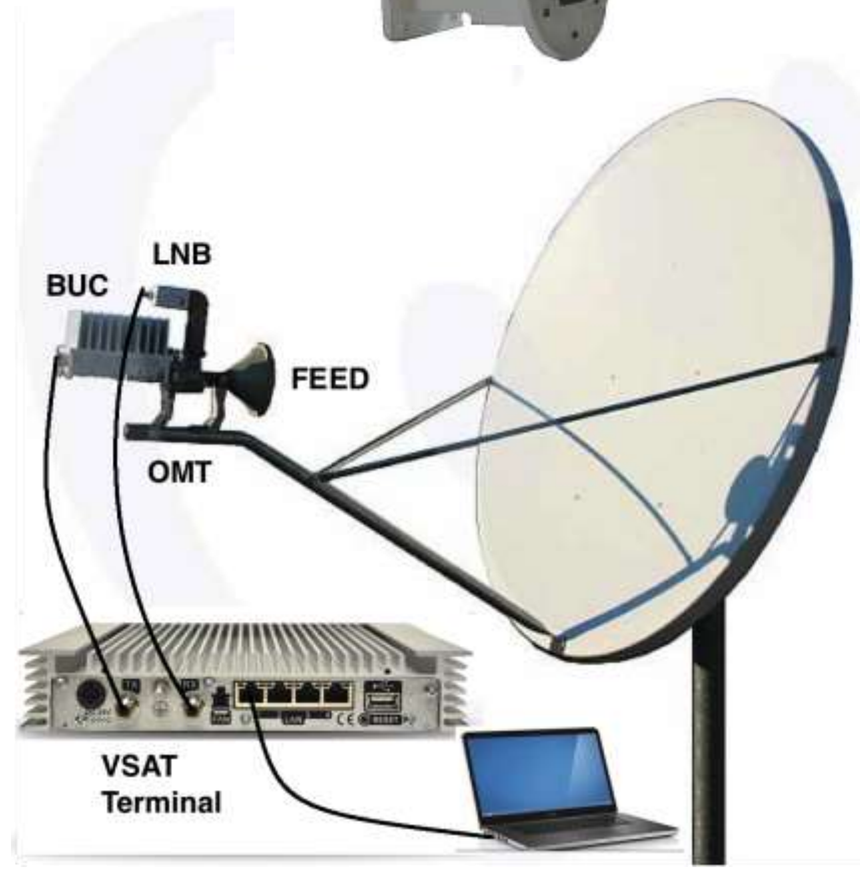
- Satellite communication can be divided in two main parts: TV Broadcasting and Data Communication. Broadcasting is one way, data is two way traffic.
- Data communication can be point to point as well as point to multipoint.
- Point to Point: one carrier from A to B, second carrier from B to A. Both sides must use the same modulation and coding. It is also called as SCPC (Single Channel Per Carrier)
- Point to Multi-point: One (or more) big carrier (Forward) from HUB to remotes, multiple small carriers (Return) from remotes to HUB. TDMA and FDM is used to share the carrier. This type of data communication is named as VSAT (Very Small Aperture Terminals)





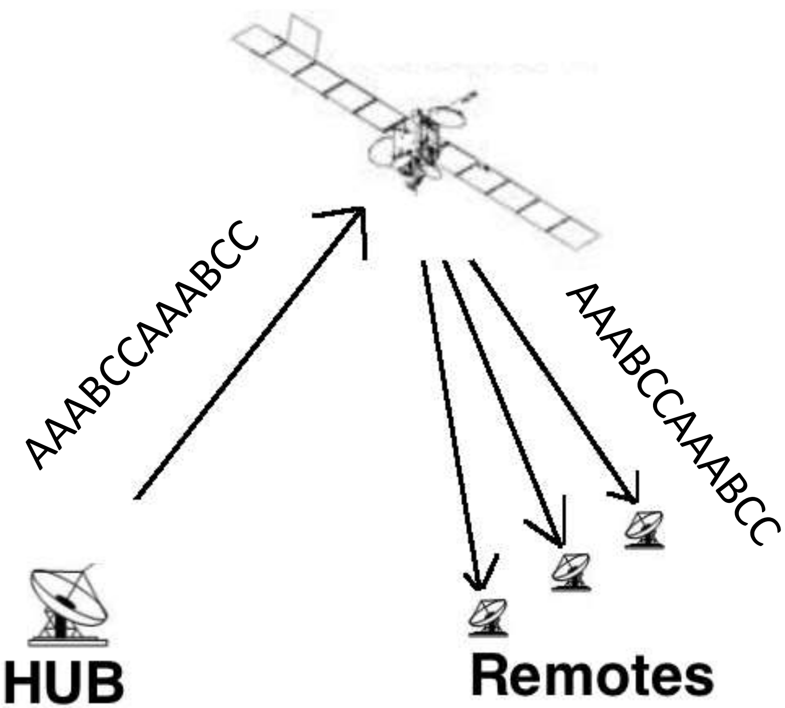
Satellite Communication
VSAT

- **VSAT (Very Small Aperture Terminal)** is acronym used for data communication network with a HUB and remotes. OMT Orthomode Transducer separates uplink and downlink signals at different polarizations using the same Feed. VSAT Modem TX port is connected to BUC and RX port to LNB using coaxial cables (RG6 or RG11). BUC Block-Upconverter changes the L band IF signal to satellite frequency (14 Gz) and power amplifies (8,16,32W). VSAT terminal Ethernet port can be connected to computer directly or a network.



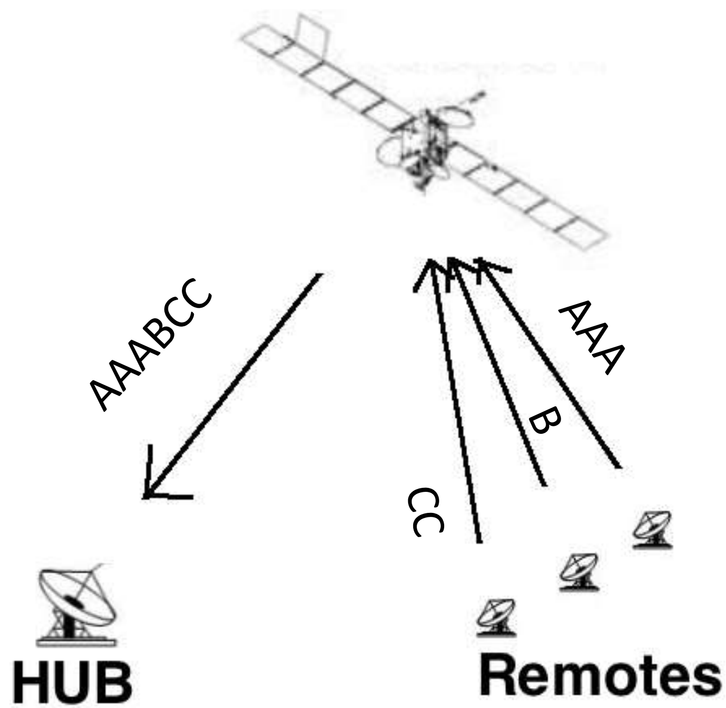
Satellite Communication
Data Communication-TDMA Forward

- TDMA (Time Devision Multiple Access) assigns time slots to each remote (A,B,C). This assignment can be fixed or dynamic. Let's assume it is fixed, A=3Mbps, B=1Mbps, C=2Mbps. Remotes receive all forward traffic coming from the HUB decodes and uses only their time slots.



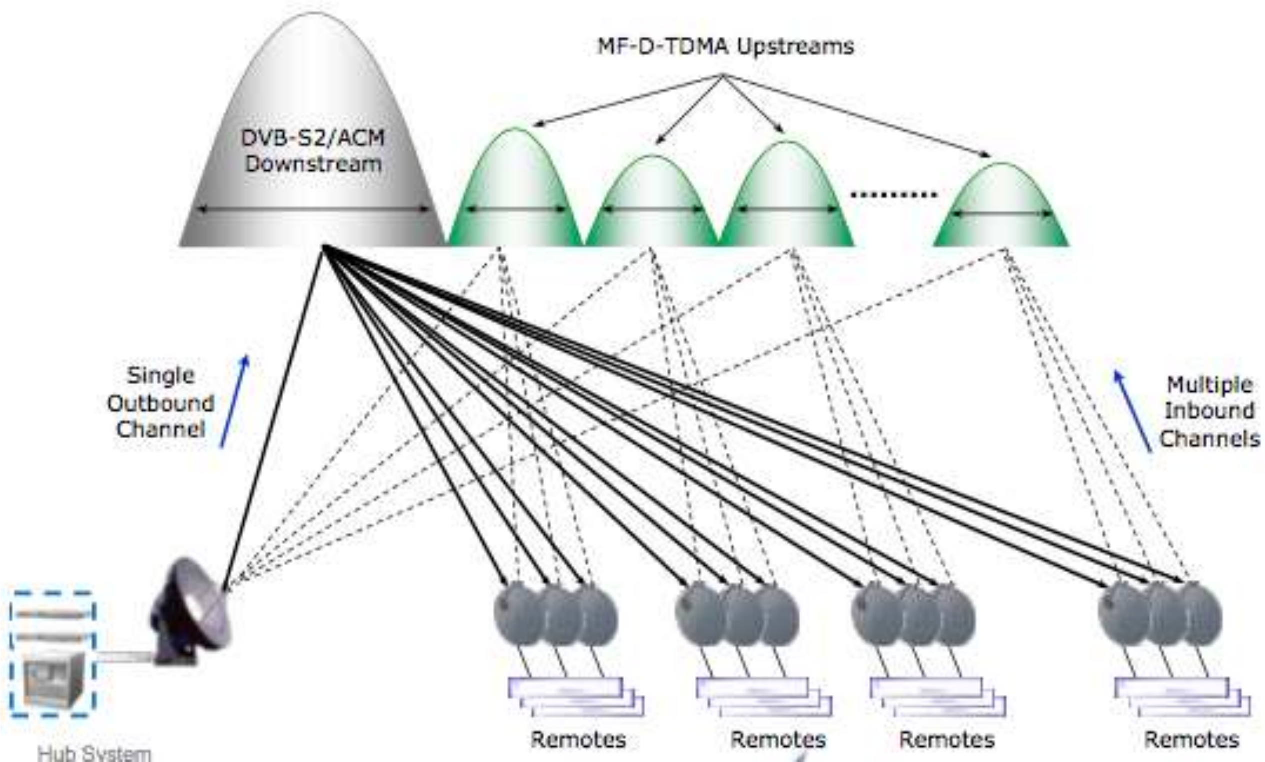
Satellite Communication
Data Communication-TDMA Return

- On the return side, defined group of remotes uplink at the same frequency (it may be dynamic). Thus time synchronization is important, otherwise uplink signal can corrupt. Location of remotes also important so that HUB can assign their time slots in such a way that when they reach to the satellite they will not overlap.



Satellite Communication
VSAT Spectrum

- There may be many return carriers at different frequencies depending number of remotes.
- There is a wide carrier for forward channel. If forward is not sufficient, additional forward carriers can be assigned to new group of remote terminals

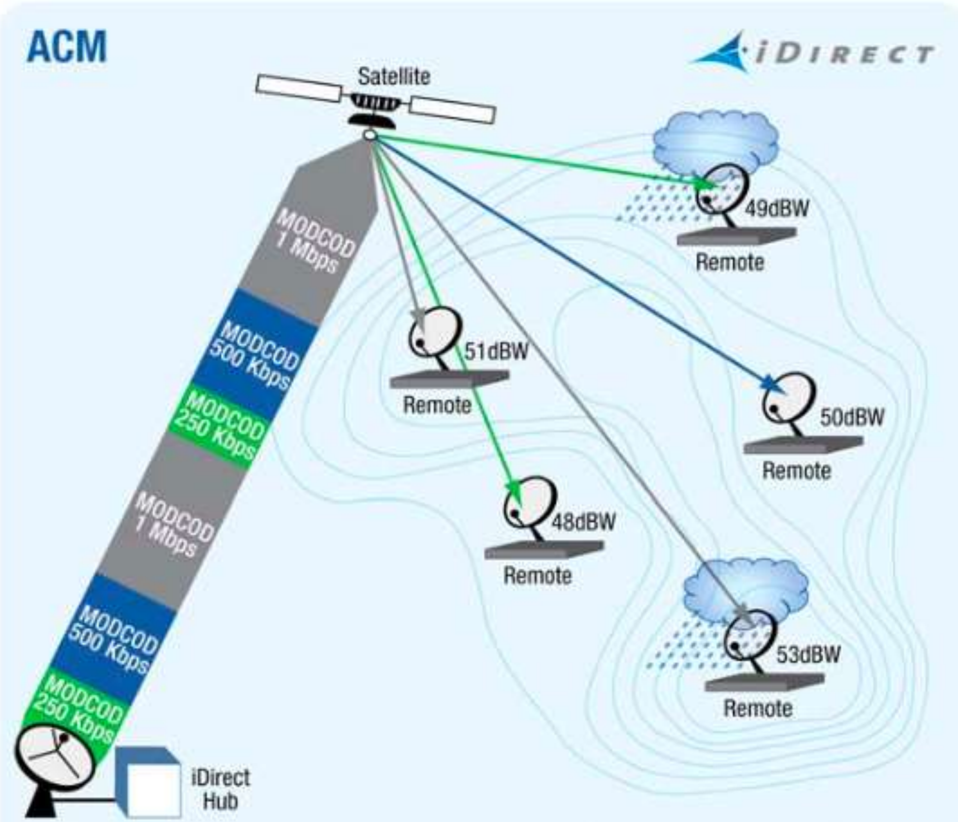


Satellite Communication Multiple Access Protocols

- How remotes will share the same bandwidth ? There are different approaches in industry: Aloha random access and Deterministic TDMA.
- D-TDMA reserves a minimum capacity for each remote. This capacity is increased dynamically by HUB according to remote data queue, CIR or QOS. Different traffic management packets can exist. The simplest one is CIR (Committed Information Rate) preserves time slots to remote without looking if used or not. M-TDMA is not very efficient for bandwidth utilization but provides the best for response time.
- Remotes uses a contention based Aloha channel for initial traffic request. HUB assigns time slots according to remote’s request and remotes transmit at its time slots. If there is no traffic there is not any resource reserved for the remote. Aloha is efficiently uses the bandwidth but my have bad response time depending on number of channels sharing the same Aloha channel

Satellite Communication
Data Communication-ACM

- ACM allows to send different MOD(8PSK, QPSK,…) and COD(1/2,2/3,3/4,…) at different frames targeting for different remotes



ACM enables each remote to achieve maximum data throughput by utilizing the most efficient coding and modulation scheme dependant upon the location within the satellite contour, antenna size, and clear sky conditions versus rain fade.

Satellite Communication
VSAT Forward Downlink Budget

- Same formulas are valid for VSAT.
- Example: 8PSK ¾, EIRP=52dBW , antenna=75cm, 11GHz, 30 Mbaud, 1.35 rolloff

Downlink			Calculations		
EIRP	52	dBW	Azimuth	166,2	deg
F	11	Ghz	Elevation	42,8	deg
longsat	42		S	37570	km
longrx	33		Tlnb	75	K
latrx	40		Ts	125,09	K
Ta	50	K	FSL	204,82	dB
NF	1		Bw	40,50	MHz
Rs	30	Msps	Gr	36,86	dB
Rolloff	0,35		C/N	15,59	dB
Seff	2,228124		Ri	66,84372	Mbps
Es/No Req	7,91	dB	Eb/No	13,41	dB
Diameter	0,75	m	Es/No	16,89	dB
			Margin	8,98	dB

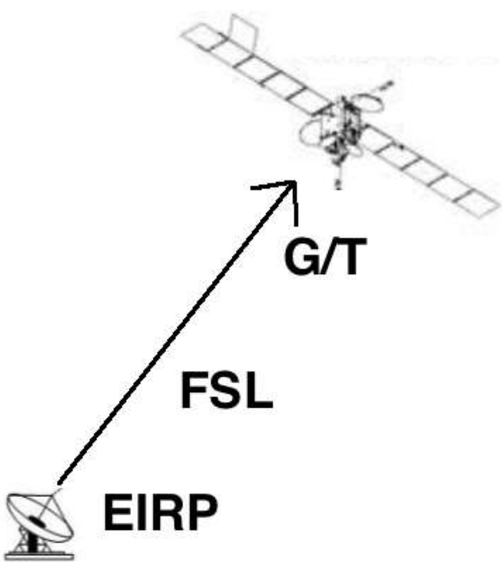
Satellite Communication
VSAT Forward Uplink Budget

- Same formulas are valid for VSAT.
- Example: HUB antenna=7m, 200W, 14GHz, BW=40.5MHz, SFD=-90dBW/m2

Uplink			Calculations		
HPA	200	W	Gtx	58,35	dBi
F	14	Ghz	EIRPu	81,36	dBW
longsat	42		S	37570	km
longtx	33		FSL	206,92	dB
lattx	40		SFD	-81,12	dBW/m2
Diameter	7,0	m	SFD margin	8,88	dB
SFDreq	-90	dBW/m2	Bw	40,50	Mhz
G/Tsat	10	dB/K	C/Nup	36,97	dB
			C/Ndown	15,59	dB
			C/Ntotal	15,56	dB

Satellite Communication
Uplink-Example

- 200W, 3.7m transmit antenna, 14GHz uplink frequency, satellite G/T=10, B=40.5Mhz, Antenna diameter is 3.7m
- Calculate uplink C/N and check **if SFD is enough for required SFD=-90 dBW/m2**



$$\boldsymbol{Gtx = 20\log(F.D) + 18.53\ dB = 52.82\ dBi}$$

$$\boldsymbol{EIRPu = 10\log(P) + Gtx = 75.83\ dBW}$$

$$S = 37570\ km, \boldsymbol{FSL = 20\log(F.S) + 92.5 = 206.9dB}$$

$$\boldsymbol{SFD = EIRPu - 10\log\left(4\pi S^2\right)} = -86.66\ dBW/m2$$

$$\boldsymbol{SFD\ margin = 3.34dB}$$

$$\frac{Cu}{Nu} = EIRP - FSL + \frac{Gsat}{Tsat} - 10\log(B) + 228.6 = 31.43dB$$

$$\frac{Cdown}{Ndown} = 13.65dB, \frac{Ctotal}{Ntotal} = 13.58dB$$

Downlink- DVB-S2 Link Budget

- EIRP=52dBW at Ankara F=11GHz, DVB-S2 8PSK 3/4, symbol rate=30000, rolloff=0.35 receive antenna=60cm,
- Required Es/No for **DVB-S2 8PSK 3/4 is 7.91** dB and **Seff=2.228124**
- Calculate C/N, Ri, BW, Eb/No, Es/No and link margin

$$\mathbf{\frac{C}{N} = EIRP - FSL + Gr - 10\log(Ts.BW) + 228.6\ dB}$$

$\mathbf{S = 37570}$ km for Ankara

$\mathrm{FSL} = \mathbf{20\log(\boldsymbol{F}.\boldsymbol{S}) + 92.5\ \boldsymbol{dB}} = 204.8\ \mathrm{dB}$

$\mathrm{Gr} = 20\log(\mathrm{F.D}) + 18.53 = 35\ \mathrm{dBi}$

$\mathbf{Ta = 50K, NF = 1, Tlnb = 290\left(10^{\frac{NF}{10}} - 1\right) = 75K\ Ts = Ta + Tlnb = 125K}$

$\mathrm{BW} = (1 + \mathrm{ro})\mathrm{Rs} = 40.5\ \mathrm{Mhz}$

$$\mathbf{\frac{C}{N} = 13.65\ dB}$$

$\mathrm{Rinfo} = \mathrm{Rs.Seff} = 66.843\ \mathrm{Mbps}$ $\qquad \mathbf{\frac{Eb}{No} = \frac{C}{N} - 10\log\left(\frac{Ri}{\boldsymbol{BW}}\right) = 11.47dB}$

$\mathbf{\frac{Es}{No} = \frac{Eb}{No} + 10\log(Seff) = 14.95dB}, \mathrm{Required}\frac{\mathrm{Es}}{\mathrm{No}} = \mathbf{7.91dB}, \mathrm{Margin} = +7\mathrm{dB}$

Satellite Orbits
TLE of Gokturk-2

GOKTURK 2
1 39030U 12073A   17010.14461809 .00000060 00000-0 17178-4 0 9994
2 39030 **98.0117** 265.3320 **0000976** 139.5301 220.5980 **14.726148682**17292

Gokturk-2 important parameters:
Mean motion: 14.726148682 rev/day => 86400/**14.726148682**/60=97.8 min/rev,

$$\boldsymbol{T = 2\pi\sqrt{\frac{a^3}{GM}}}$$ GM=398600,4418 km3/s2

$$\boldsymbol{a = \sqrt[3]{GM(T/2\pi)^2}}$$ =7031km

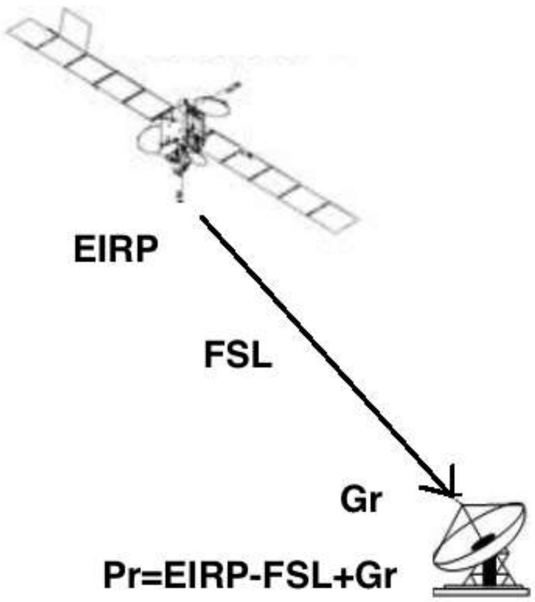
remember Earth Radius 6378km, means 653 km from Earth Surface

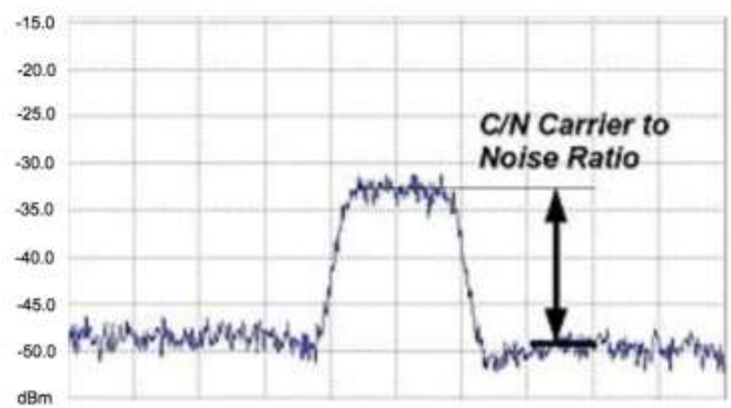
Inclination: **98.0117** degree, polar orbit

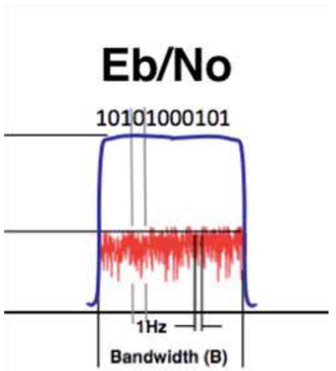
Eccentricity: **0.0000976**, too small, almost circular orbit

Satellite Communication
Downlink Link Budget

- What is the target of downlink Link Budget calculations:
- **given a satellite**, how can I select my receiver parameters such as Antenna, LNB, to receive the TV or Data signal from the satellite
    1. **First calculate C/N**
    2. **Calculate Eb/No, Es/No**
    3. **Check if within requirements**







DVB-S2

- Data
- Encoder
- Modulator
- Channel
- Demodulator
- Decoder
- Data

ETSI EN 302 307 V1.1.1 (2005-03)

European Standard (Telecommunications series)

**Digital Video Broadcasting (DVB);
Second generation framing structure, channel coding and modulation systems for Broadcasting, Interactive Services, News Gathering and other broadband satellite applications**

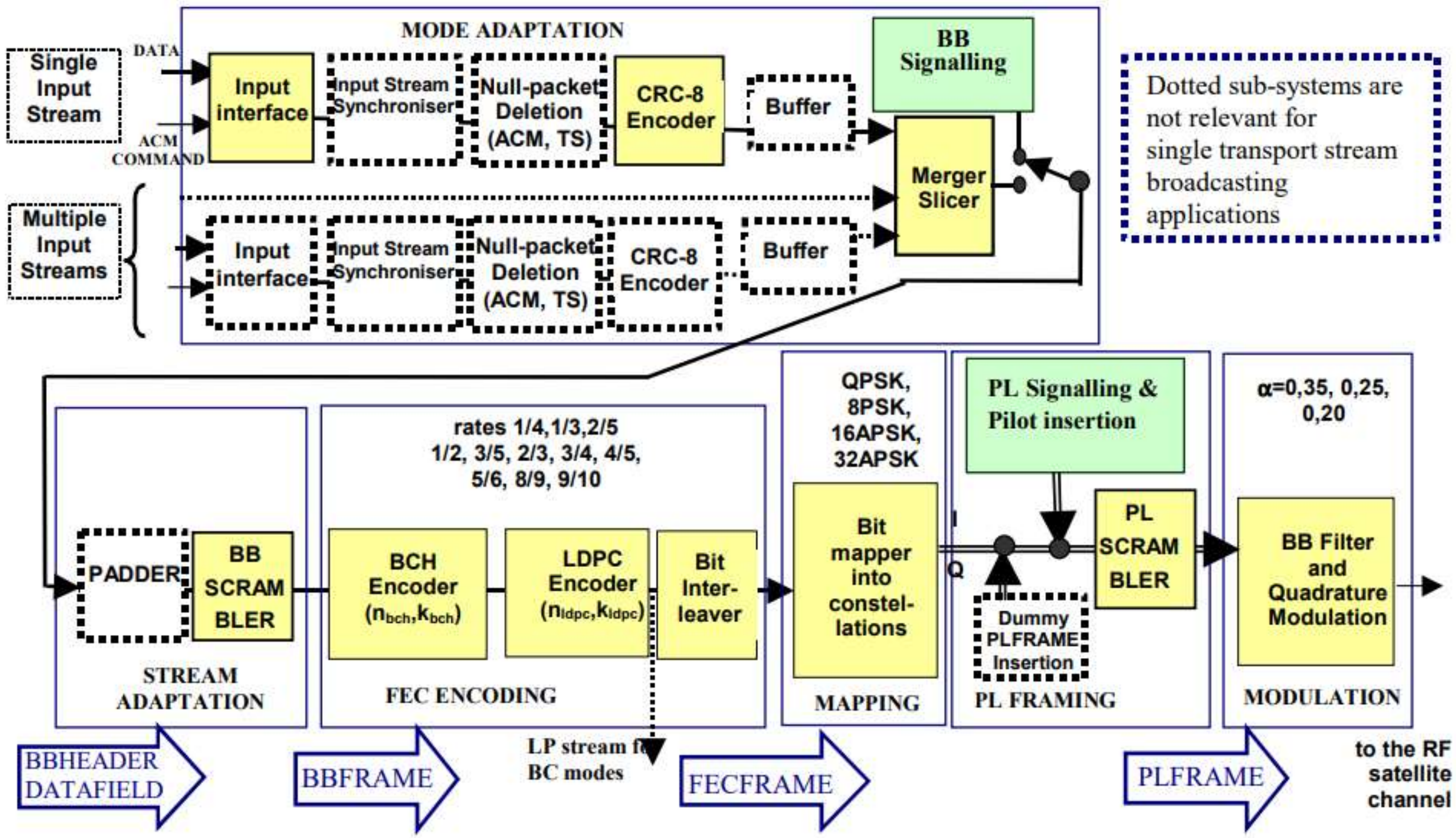


Figure 1: Functional block diagram of the DVB-S.2 System

DVB-S2

- Data
- Encoder
- Modulator
- Channel
- Demodulator
- Decoder
- Data