Satellite Telecommunication Overview

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Outline

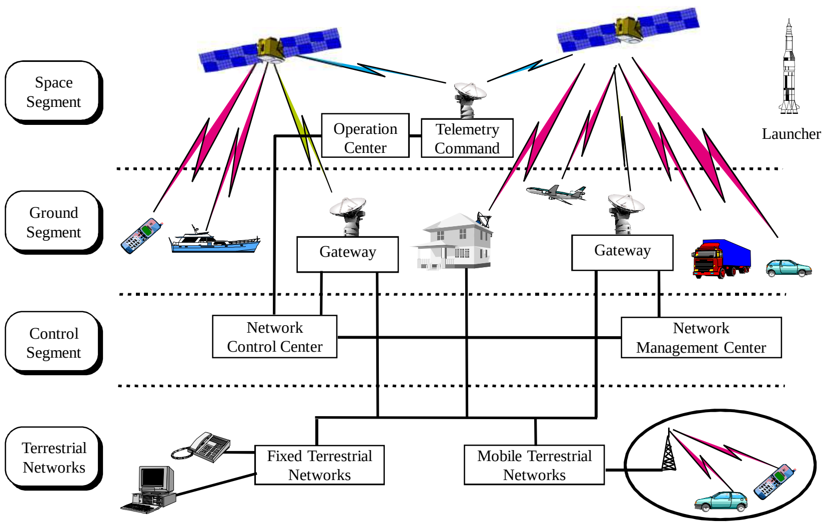
- **Space systems**
  - Brief history since 1957
  - Elements of a space system
  - Applications based on space systems
- **Satellite orbit**
  - Kepler's laws of planetary / satellite motion
  - Orbit of a satellite
  - Two Line Element (TLE) data and orbital coordinate systems
- **Telecommunication satellite**
  - Platform & telecom payload
  - Project management
  - Supply chain and business plan

History

Satellite : *Natural or artificial object that revolves around a larger astronomical object, as a planet*

- 1945 Publication of Arthur C. Clarke's essay about „Extra Terrestrial Relays“
- 1957 1st satellite Sputnik-1 (USSR)
- 1958 1st American orbital launch Explorer-1 (USA)
- 1959 1st human made satellite to orbit the moon Luna-1 (USSR)
- 1960 1st weather satellite Tiros-1 (USA)
- 1961 1st man in space Vostok-1 Yuri Gagarin (USSR)
- 1962 1st live transatlantic telecast with Telstar-1 (USA)
- 1965 1st French orbital launch Asterix (France)
- 1965 1st commercial geostationary satellite Intelsat-1 (240 phone channels or 1 TV channel)
- 1966 1st spacecraft to soft-land on the moon Luna-9 (USSR)
- 1968 1st staffed spacecraft to orbit the moon Apollo-8 (USA)
- 1969 1st staffed soft landing and walk on the moon Apollo-11 Neil Armstrong (USA)
- 1970 1st Japanese orbital launch Osumi (Japan) and 1st Chinese orbital launch DFH-1 (China)
- 1971 1st space station Salyut-1 (USSR)
- 1975 1st international docking Apollo-18/Soyuz-19 (USA/USSR), European Space Agency (ESA)

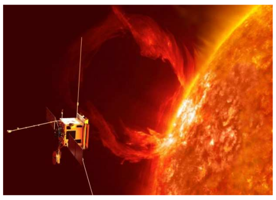
Space System



Sciences & Exploration

Life science

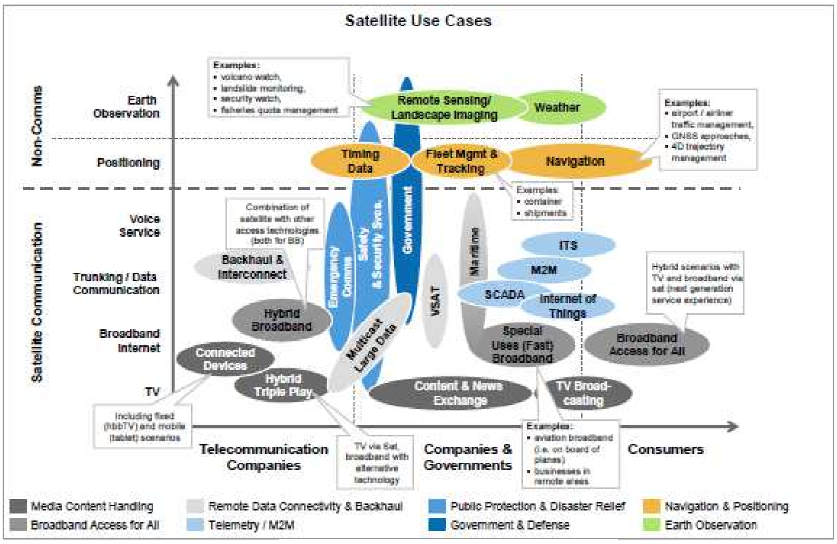
Sciences



Exploration

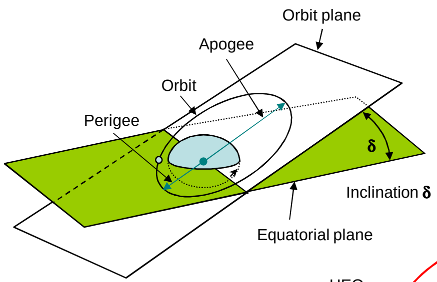
Astrophysics

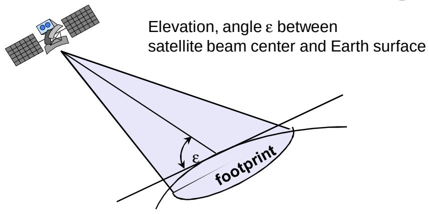
Telecommunications & Navigation & Earth Observation



Source: booz&co.

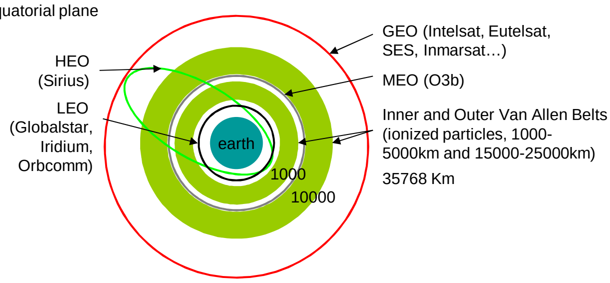
Satellite Orbits





Kepler laws

- The orbit is an ellipse with the Earth at one of the two foci
- A line joining the satellite and the Earth sweeps out equal areas during equal intervals of time
- The square of the orbital period is directly proportional to the cube of the semi-major axis of the orbit

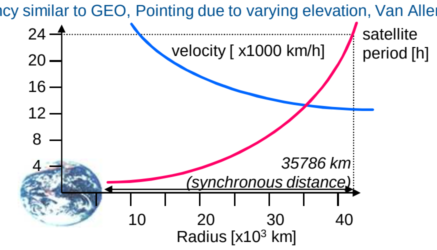


Satellite orbits

LEO: Low Earth Orbit (500-1500km)
GEO: Geostationary orbit (36000km)
MEO: Medium Earth Orbit (6000-23000km)
HEO: Highly Elliptical Orbit

Satellite Orbits for Telecommunications

- **Geostationary orbit (GEO) 35768km with zero inclination**
  - Satellite speed ~ 3km/sec with orbital period 24 hours
    - \+ Limited number of satellites, Large footprint, Fixed antenna positions
    - \- Low elevation in areas with latitude above 60° , High transmit power, High latency (275ms)
- **Low Earth Orbit (LEO) 160-2000km / Medium Earth Orbit (MEO) 2000km -35786km**
  - Satellite speed 8km/sec to 3 km/sec with orbital period 90 min to 24h
    - \+ Global coverage, Low consumption equipment, Low latency (5-10ms for LEO, 70-80ms for MEO)
    - \- High number of satellites, Satellite handover, Pointing due to varying elevation
- **High Elliptical Orbit (HEO) with apogee above 35786km**
    - \+ Regional coverage with 3 satellites, High elevation even at high latitudes
    - \- Power and latency similar to GEO, Pointing due to varying elevation, Van Allen Belts crossing

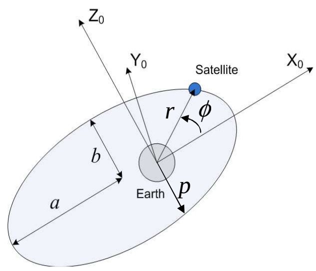


Kepler's Laws

- **History**
  - Extensive astronomical planetary measurements performed by Tycho Brahe (until 1601)
  - Publication by Johannes Kepler of planetary motion laws in solar system (1609, 1618)
  - Newton's theory of gravity in *Philosophiæ Naturalis Principia Mathematica* (1687)

1. $r = \dfrac{p}{1 + e\cos(\phi)}$ 2. $\boldsymbol{r} \times \dfrac{d\boldsymbol{r}}{dt} = \text{const}$ 3. $\dfrac{T^2}{a^3} = \text{const}$

e : eccentricity p : semi-latus rectum T : period a : semi-major axis



Gravitational force / Newton's 2nd law

$$\boldsymbol{F} = -\frac{GM_E m\boldsymbol{r}}{r^3} \qquad \boldsymbol{F} = m\boldsymbol{a} = m\frac{d^2\boldsymbol{r}}{dt^2}$$

$G = 6.672\times10^{-11}\,\text{Nm}^2/\text{kg}^2 \qquad M_E = 5.98\times10^{24}\,\text{kg}$

$$\Downarrow$$

$$\frac{d^2\boldsymbol{r}}{dt^2} + \frac{\boldsymbol{r}}{r^3}\mu = 0$$

$p = \dfrac{h^2}{\mu} \qquad \mu = 3.983\times10^5\,\text{km}^3/\text{s}^2 \qquad h$: angular moment

Eccentricity: 0 for circular orbit, in]0,1[for elliptical orbit, 1 for parabolic orbit, > 1 for hyperbolic orbit

Two Line Element Data (TLE)

```
ISS (ZARYA)
1 25544U 98067A   08264.51782528 -.00002182  00000-0 -11606-4 0  2927
2 25544  51.6416 247.4627 0006703 130.5360 325.0288 15.72125391563537
```

LINE 1

Field	Columns	Content	Example
1	01-01	Line number	1
2	03-07	Satellite number	25544
3	08-08	Classification (U=Unclassified)	U
4	10-11	International Designator (Last two digits of launch year)	98
5	12-14	International Designator (Launch number of the year)	067
6	15-17	International Designator (Piece of the launch)	A
7	19-20	Epoch Year (Last two digits of year)	08
8	21-32	Epoch (Day of the year and fractional portion of the day)	264.51782528
9	34-43	First Time Derivative of the Mean Motion divided by two	-.00002182
10	45-52	Second Time Derivative of Mean Motion divided by six (decimal point assumed)	00000-0
11	54-61	BSTAR drag term (decimal point assumed)	-11606-4
12	63-63	The number 0 (Originally this should have been "Ephemeris type")	0
13	65-68	Element number	292
14	69-69	Checksum (Modulo 10)	7

LINE 2

Field	Columns	Content	Example
1	01-01	Line number	2
2	03-07	Satellite number	25544
3	09-16	Inclination [Degrees]	51.6416
4	18-25	Right Ascension of the Ascending Node [Degrees]	247.4627
5	27-33	Eccentricity (decimal point assumed)	0006703
6	35-42	Argument of Perigee [Degrees]	130.5360
7	44-51	Mean Anomaly [Degrees]	325.0288
8	53-63	Mean Motion [Revs per day]	15.72125391
9	64-68	Revolution number at epoch [Revs]	56353
10	69-69	Checksum (Modulo 10)	7

Geocentric equatorial coordinate system (GEC)

Fixed rectangular coordinate system (moves through the space, but does not rotate)

Ω - right ascension – angle from positive x-axis to the point P where satellite comes out of the equatorial plane

i – inclination of the orbit – angle between orbital plane and equatorial plane

ω – argument of perigee – angular distance between perigee and the point P

http://celestrak.com/NORAD/elements/

Example

- **Calculate rotating coordinates for ISS at the time when TLE data are taken**

  TLE Data for ISS (obtained on OCT 26, 2013):

  1 25544U 98067A 13298.22562148 .00015844 00000-0 27472 -3 0 8812

  2 25544 51.6491 184.0276 0002282 77.2230 68.9667 15.4953682854871
- **TLE data vs. Orbital Mechanics**
  - Eccentricity (*e*)
  - Mean motion in rev/day (M_m) vs. Semi-major axis (*a*)
  - Mean anomaly (*M*) vs. Time at the perigee (t_p)
  - Right ascending node angle (Ω)
  - Inclination (*i*)
  - Argument of the perigee (*ω*)
- **Questions**
  - Semi-major axis *a = ?*
  - Eccentric anomaly *E = ?*
  - Orbital coordinates x_0 = ? y_0 = ?
  - ⇨ Conversion in rotating coordinates x_r, y_r, z_r

$$T^2 = \left[\frac{23\text{h }56\text{min }4.1\text{sec}}{M_m}\right]^2 = \frac{4\pi^2}{\mu}\cdot a^3$$

$$M = \eta(t - t_p) \qquad \eta = \frac{\mu^{1/2}}{a^{3/2}}$$

$$\tan E \approx \frac{\sin M}{\cos M - e} \quad \textit{for e small}$$

$$r_0 = a\left[1 - e\cos(E)\right]$$

$$\phi_0 = \cos^{-1}\left[\frac{a(1-e^2) - r_0}{er_0}\right]$$

$$x_0 = r_0\cos(\phi_0);\ y_0 = r_0\sin(\phi_0)$$

Example - Solution

- **Calculate rotating coordinates for ISS at the time when TLE data are taken**

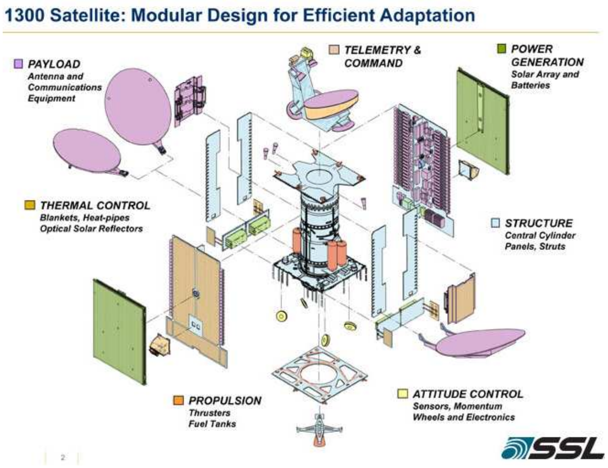
  TLE Data for ISS (obtained on OCT 26, 2013):

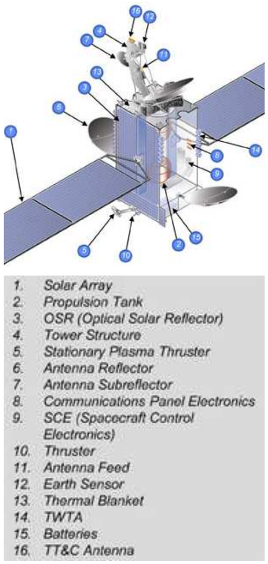
  1 25544U 98067A 13298.22562148 .00015844 00000-0 27472 -3 0 8812

  2 25544 51.6491 184.0276 0002282 77.2230 68.9667 15.4953682854871
- **TLE data vs. Orbital Mechanics**
  - *e=0.0002282*
  - M_m=15.49536828 => a^3=3.983*10^5/(4*π^2)*(86164/15.495)^2 => a=6783.8km
  - *M*= 68.9667°, *t=0.22562148day => t=324.89min, t_p=t-M*(a^3/3.983*10^5)$^{1/2}$*=307.14min
  - *Ω=184.0276°*
  - *i=51.6491*
  - *ω=77.223°*
- **Questions**
  - Eccentric anomaly *E= 1.204173*
  - Orbital coordinates x_0 *=2430.21km*, y_0 *=6332.95km*
  - Rotating coordinates x_r *=-4201.9km*, y_r *=-4428.57km*, z_r *=2957.01km*

    using Julian Day *JD=2456591 =>* $\Omega_e T_e$*=114.9888894° [360°]*

Satellite Platform



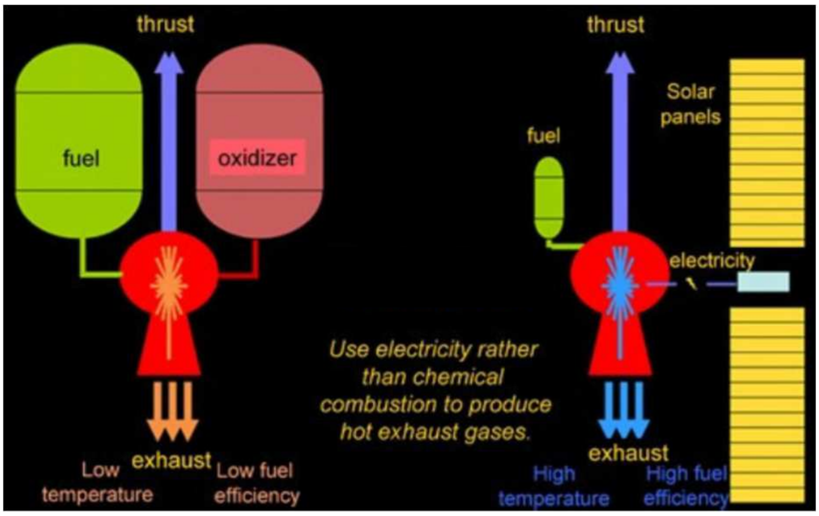


TWTA: Travelling Wave Tube Amplifier
TT&C: Telemetry, Tracking & Control

Satellite Platform Subsystems

- Structure: carriage of the other subsystems
  - Mechanical functions (rigidity, deployment), Geometric functions (surface, volume), Protection
- Thermal control: equipment qualification limits
  - Active devices (heaters), Passive devices (blankets, radiators)
- Electric Power Supply (EPS): platform and payload requirements
  - Primary sources (Solar cells), Secondary sources for eclipses (Batteries)
- Telemetry, Tracking and Command (TTC) : command and control data transmission
  - Low data rates with high availability
- On-Board Data Handling (OBDH): command and control data management
  - Standardized data processed by an on-board computer
- Attitude and Orbit Control Subsystem (AOCS): Spin or 3-axis stabilization
  - Attitude sensors, Actuators
- Propulsion system: high power thrusters for orbit changes, low power thrusters for control
  - Chemical propulsion - Electrical propulsion

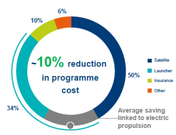
Satellite Propulsion Techniques



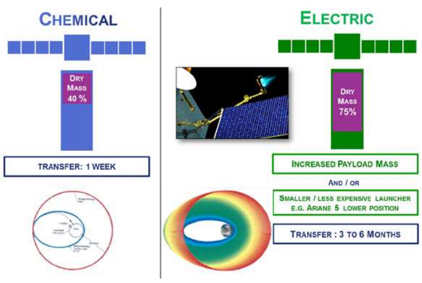
Electric Propulsion Platforms

	Compact satellite, 8 kW payload power			Medium satellite, 9.5kW payload power			Large satellite, 11 kW payload power		
Launch Vehicle	**Full electric**	**Hybrid**	**Full chemical**	**Full electric**	**Hybrid**	**Full chemical**	**Full electric**	**Hybrid**	**Full chemical**
Falcon 9	1833	2981	3915	2470	4016	5218	3106	5051	6524
Ariane 5	1795	2659	3491	2419	3583	4655	3042	4506	5820
Proton	1739	2235	2935	2343	3011	3913	2947	3787	4891

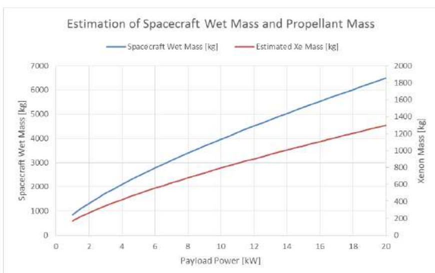
Wet mass in kg for fixed dry mass and 20 years life, Source: Turksat 2019



Source: Eutelsat



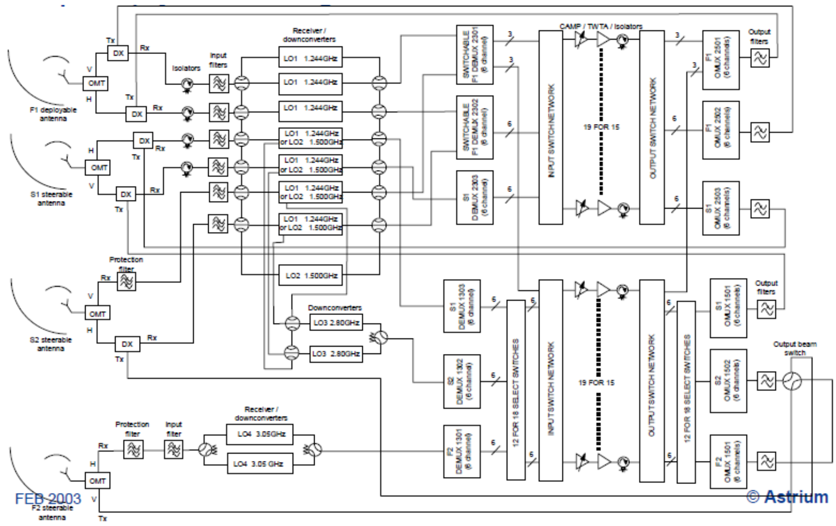
Source: Airbus Defense & Space, 2018



Source: Safran Aircraft Engines 2019

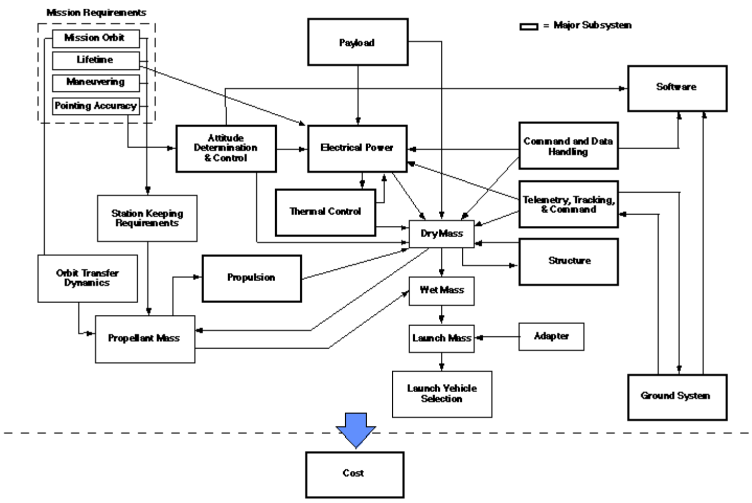
Electric Orbit Raising (EOR) in 4 months for Eutelsat 172B (3.55t, 13kW)

Example of Telecom Payload (Hellasat-2)



OMT: Orthogonal Mode Transducer   DX: Diplexer   LO: Local Oscillator   CAMP: Channel Amplifier
DEMUX: Demultiplexer   TWTA: Travelling Wave Tube Amplifier   OMUX: Output Multiplexer

Satellite Project



Payload (Primary mission data) - Attitude and Orbit Control (Pointing accuracy) - Propulsion (Orbit maintenance and control)
Power (Required satellite power) - Communication (Link with ground stations, Satellite tracking)
Command and Data Handling (Command distribution, Data processing, storage and formatting) - Thermal (Temperature control)
Structure (Carriage, support and alignment of the satellite equipment, Launcher interface structure)

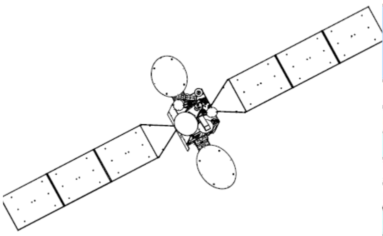
Satellite Design

- **Constraints on the bus to accommodate the customer-specified payload**
  - Location of antenna feeds on the Earth deck pre-defined for stability, minimum loss…
  - TWTA mounting locations to adapt to heat pipe panel design
  - Location of OMUX, relatively big in size, to minimize the RF loss up to the antenna
- **System performance requirements**
  - Mass&Power Budgets (5~10% margin added at the beginning of the design)
  - Thermal Dissipation Budget
  - Link Budget
- **Environmental requirements**
  - Ground: cleanness, handling
  - Space: thermal sensitivity, vacuum sensitive units, Corona arcing, electrostatic discharge
  - Components for space-based applications

Parameter	*COTS*	*Rad-Tolerant*	*Rad-Hardened*
Radiation tolerance	≤ 1 krad (Si)	15 to 50 krad (Si)	≥ 100 krad (Si)
Qualification	Industrial temperature range (-40°C to +85°C)	Characterized for radiation tolerance levels	NASA EEE-INST-002 component qualification
Mission duration	Short	Longer	Extremely long
Mission type	Not used in critical manned missions	Manned	Manned
Orbit	Used in some LEO missions	GEO, MEO, LEO	GEO, MEO, LEO
Cost	Less expensive	More expensive	Significantly more expensive

Source: RF Signal Chain and Components for Space-Based Satcom Applications, B. Chandhoke, Microwave Journal, 2024

Example of Mass & Power Budgets

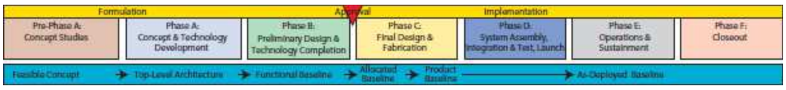


Items	MASS (kg)
Payload	470
Platform	1500
Margin	50
Satellite Dry Mass	2020
Helium	7.6
15 years MON-1	1945.8
15 years MMH	1176.6
Satellite Launch Mass	**5150**

Power Allocation	GEO EOL		
	Autumn Equinox	Summer Solstice	Eclipse
Payload	5304.0	5304.0	5304.0
Platform	799.3	617.5	435.7
Total Power Req.	6103.2	5921.4	5739.6
Battery Charging	758.6	73.7	0.0
PCU Low Level	51.9	51.9	51.9
Total Power Consu	6913.8	6047.1	5791.5
Solar array, EOL	7756.0	7009.8	-
One section failure	323.2	292.1	
Power Margin(W)	519.1	670.6	-
Margin (%)	7.51%	11.09%	-
Battery Capacity @80%DOD, EOL	-	-	7080.0
Harness loss	-	-	329.0
Power margin (W)	-	-	959.5
Battery DOD, EOL	-	Nominal	67.21%
	-	Worst Case	69.13%

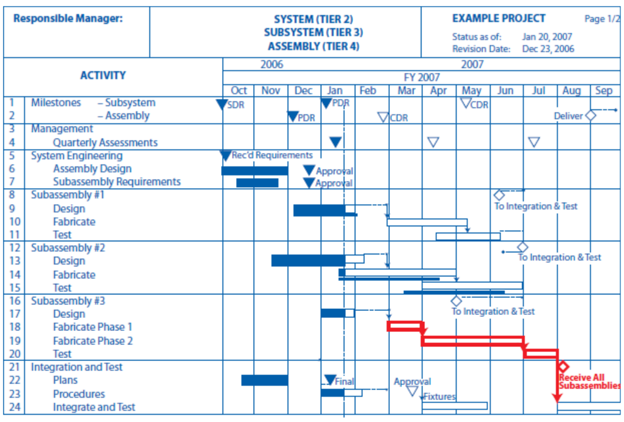
Source: Nigcomsat-1, CAST, 2006

Development Phases

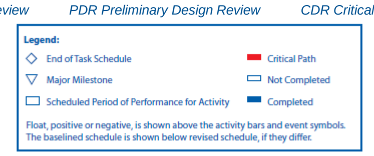


- **Pre-Phase A Concept Studies:** draft mission, desired system, technology needs
  - Feasible system concepts with study reports, simulations, analysis, models, mockups
- **Phase A Concept and Technology Development:** final mission, system-level requirements, technology developments
  - System concept definition with simulations, analysis, models, mockups, trade study definition
- **Phase B Preliminary Design and Technology Completion:** initial baseline, preliminary design
  - Specification, interface documents, trade study results, end products with mockups, prototypes
- **Phase C Final Design and Fabrication:** final designs, hardware fabrication, software code
  - End product detailed designs, end product component fabrication, software development
- **Phase D System Assembly, Integration and Test, Launch:** transition to use
  - Operations-ready system end product with supporting related enabling products
- **Phase E Operations and Sustainment:** mission operations plan
  - Desired system
- **Phase F Closeout:** Systems decommissioning, analyses of the returned data
  - Product closeout

Gantt Chart

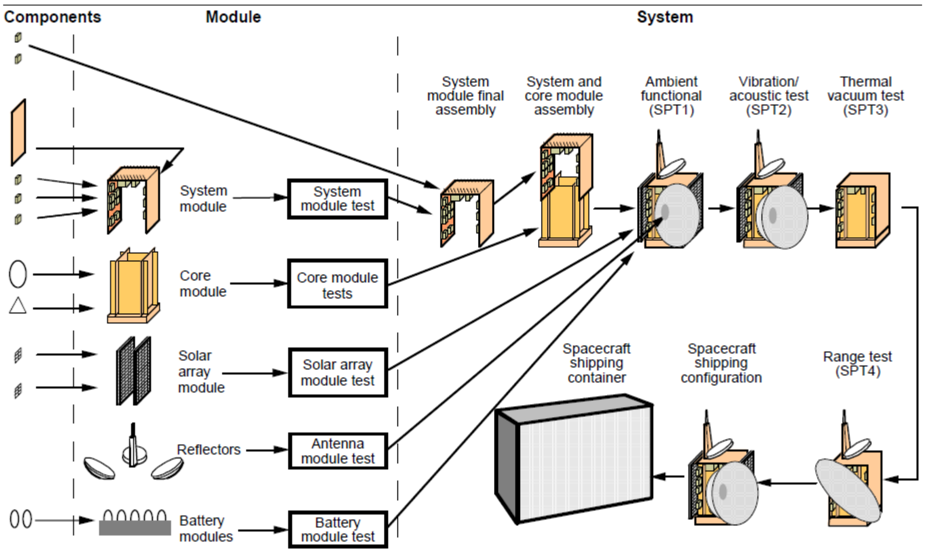


SDR System Definition Review PDR Preliminary Design Review CDR Critical Design Review



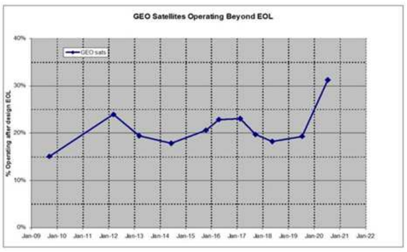
Source: NASA Systems Engineering Handbook

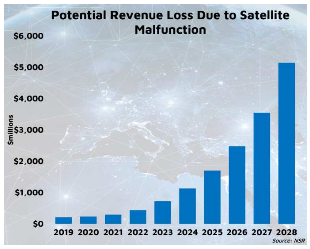
Assembly, Integration, Test (AIT)

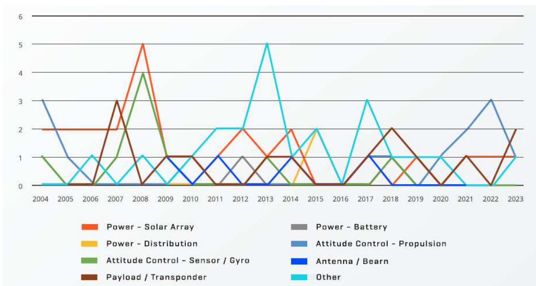


SPT: System Performance Test

Satellite End of Life (EOL)





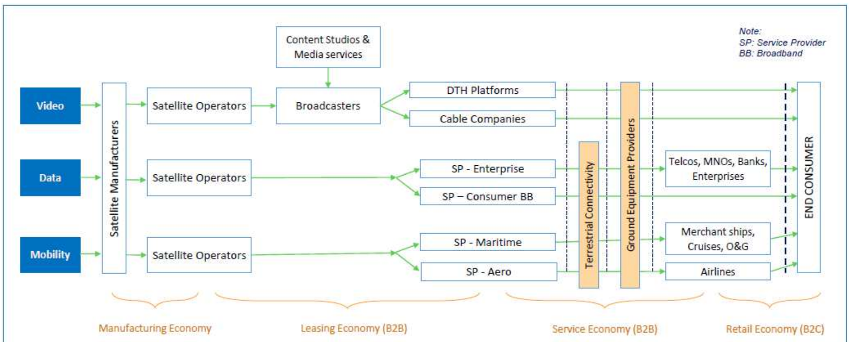


Source: Slingshot Aerospace, 2024

Space Economy

- Investors
  - Governments as operator or consumer for public services, human space flight, science and exploration, security and defense
  - Private industry for the development of commercial platforms, small launchers, personal spaceflight systems
  - Venture capital funds and business angels for technology startups and new space companies
  - Equity funds for the acquisition and consolidation of the telecommunications operators
  - Banks through loans to operators or industry
- Business models
  - Institutional business model for programs of strategic or political importance where agencies are procuring space systems from the manufacturing industry (e.g. exploration)
  - Government owned, company operated (GOCO) where operations of the system and sale of the services are granted to an operator through a convention of use (e.g. China Satcom)
  - Private funded initiative where the private operator invests for the infrastructure and sales the services to the public partner in the frame of a concession contract (e.g. Skynet 5)
  - Co-ownership model where the public and the private partners jointly invest and own a space system addressing both the public needs and the commercial market (e.g. TerraSAR-X)
  - Private business (e.g. telecommunications)
  - Value Added Services model with free of charge satellite data (e.g. GPS)

Supply Chain for Satellite Communication

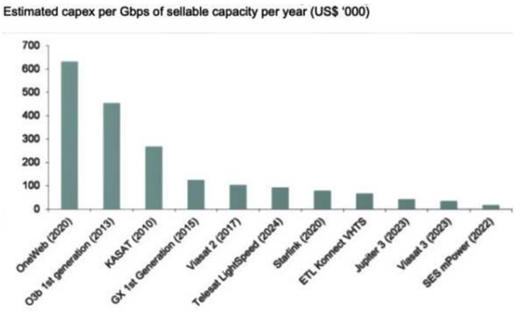


SLA:Service Level Agreement to provide Committed Information Rate (CIR) for a defined uptime (availability)

Source: NSR

- **CAPEX (capital expenditure): cost of the equipment with installation**
- **Traffic: estimation of the subscribers input and output data rates on peak hour**
- **PEB (Power Equivalent Bandwidth): maximum of consumed bandwidth and power**
- **OPEX (operational expenditure) for the traffic: amortization, maintenance and operation**
- **Revenues: ARPU (Average Revenue Per User) for all the users deducting the expenses**

Satellite Operator Business Plan



**Data: Exane/BNPP Estimates April 8 2021*

- **Service Level Agreement (SLA): Committed Information Rate (CIR) for a defined availability**
  - Inflexible capacity mainly defined during design process
  - High capacity costs compared to marginal sales cost to update or add consumers
  - Perishable inventory as power and frequency spectrum cannot be stored
  - Heterogeneous consumers in type and size, geographically, with or without gateways
  - Variable (day and nigh usage, local time-zone) and uncertain (single events) demand

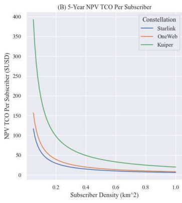
Constellation Cost per Subscriber

- Cost model
  - CAPEX: Ground segment, Digital infrastructure, Spectrum, Regulation fees
  - OPEX: Operational staff, R&D, Marketing and customer acquisition, launch&satellite amortization

Parameter	Type	Starlink Cost (US$ Millions)	Starlink Source	OneWeb Cost (US$ Millions)	OneWeb Source	Kuiper Cost (US$ Millions)	Kuiper Source
Ground Station	Capex	81.2	Author calculations from SES (2019)	47	Author calculations from SES (2019)	33	Author calculations from SES (2019)
Digital Infrastructure	Capex	6.2	Author calculations from Oughton et al.,(2019)	2.5	Author calculations from Oughton et al.,(2019)	3.6	Author calculations from Oughton et al.,(2019)
Spectrum Cost	Capex	125	Assumption	125	Assumption	125	Assumption
Regulation Fees	Capex	0.7	Calculations from FCC (2021)	0.7	Calculations from FCC (2021)	0.7	Calculations from FCC (2021)
Cost of Operational Staff	Opex	60	Calculations from SES (2019)	7.5	Calculations from SES (2019)	60	Calculations from SES (2019)
Cost Overhead per R&D	Opex	7.5	Calculations from SES (2019)	7.5	Calculations from SES (2019)	7.5	Calculations from SES (2019)
Marketing and Customer Acquisition Cost	Opex	50	Assumption	50	Assumption	50	Assumption
Launch Cost Per Satellite	Opex	0.5	Author calculations from Jones (2018)	2.0	Author calculations from Jones (2018)	1.5	Author calculations from Jones (2018)
Cost of each Satellite	Opex	0.25	Assumption	0.25	Assumption	0.25	Assumption

- 5-Year Net Present Value Total Cost of Ownership (NPV TCO) per subscriber

Parameter	Starlink	Kuiper	OneWeb	Unit
Simulated Satellites	5,040	720	3,240	-
Satellite Mass	260	147.5	260	kg
Downlink Frequency	13.5	13.5	17.7	GHz
Bandwidth	0.25	0.25	0.25	GHz
Channels	8	8	8	-
Aggregate Bandwidth	2	2	2	GHz
System Temperature	290	290	290	K
EIRP	67.7	68.3	73.1	dBm
Receiver Antenna Gain	37.7	38.3	43.1	dBi
Altitude	550	610	1,200	km
Minimum Elevation Angle	40	35.2	55	Deg
Antenna Diameter	0.7	0.75	1	m
Modulation Scheme	16	16	16	APSK
Frequency Reuse Factor	2	2	2	-
Satellite Lifespan	5	5	5	-



1% of user adoption rate (1/20 active user)

Source: A Techno-Economic Framework for Satellite Networks Applied to Low Earth Orbit Constellations: Assessing Starlink, OneWeb and Kuiper, O. B. Osoro & all, IEEEAccess 2021

Example of Satellite Backhauling Business Plan

- **CAPEX**
  - Teleport with redundancy (2 HUB, Installation) 600k$
  - 100 cells with eNodeB (30/70% new/existing site at 60/20k$) and VSAT (4k$) 3600k$
- **Monthly traffic**
  - 230 subscribers per cell (population 1500, share 17%, penetration 90%)
  - 483GB of monthly output traffic per cell (user package 3.5GB, mean consumption 60%)
  - 1.44Mbps of output data rate per cell on peak hour (60% of users, 28 days/30, 16 hours/24)
  - 160~170Mbps of total data rate (output to input ratio 10 for LTE, 5 for small cell)
- **OPEX per month**
  - Equipment amortization on 5 years (20% of the CAPEX) 70k$/month
  - Maintenance (15% of the CAPEX) 52.5k$/month
  - Network operation (24*7) 17.5k$/month
  - 74MHz satellite bandwidth 100k$/month and teleport connection to network core 20k$/month
- **Revenues per month**
  - Expenses of 260k$/month with an HTS for revenues of 552k$/month (ARPU 24$/month)