Introduction to Aerospace Engineering

Lecture slides

Introduction to Aerospace Engineering AE1102

Dept. Space Engineering

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Ground systems and operations

TU Delft

Part of the contents of this presentation originates from the lecture "Space Engineering and Technology I, Part I" (ae1-801/1), by R. Hamann.

These two lecture hours deal with the space mission and the payload (not so much the actual vehicle).

Overview

- Ground systems
- Operations
- Ground track and visibility
- Communication

Learning goals

The student should be able to:

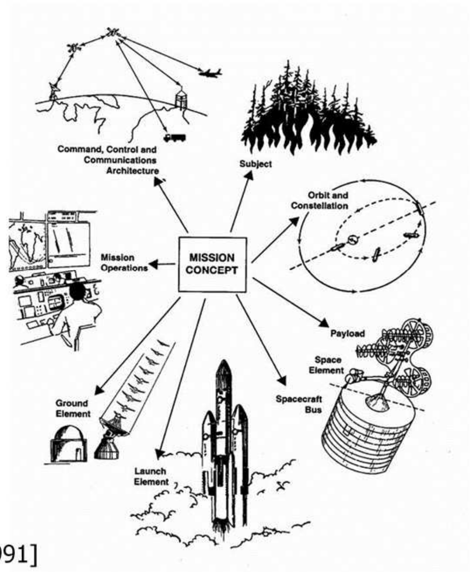
- make a first-order estimate of the received power in a communication link between a ground station and a satellite
- describe the elements of ground stations and operations, and how they interact/interfere with other elements of a space mission
- describe and explain the concept of a ground track, and its role in mission design
- Make a rough estimate of the available communication time between a ground station and a satellite

Lecture material:
- these slides (incl. footnotes)

Ground system

Ground segment:
- ground system
- mission operations

Ground system:
- ground station(s)
- control centre(s)
- communication network

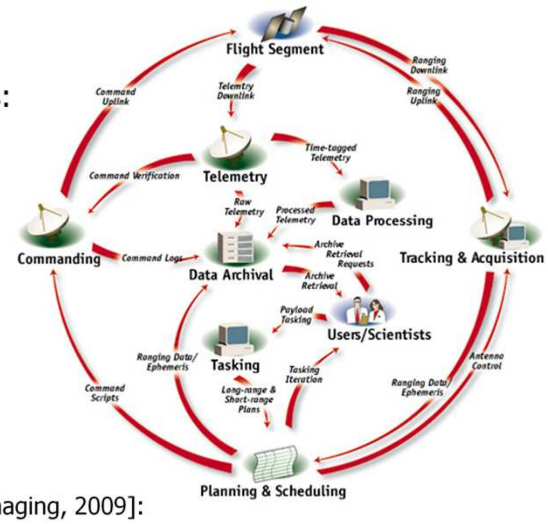


[Wertz & Larson, 1991]

The control center can be located at a single location, but it can also be split up over a mission control centre, a satellite control center and a payload control center (at various locations).

Ground system (cnt'd)

Ground system main functions:
- spacecraft tracking and acquisition
- telemetry reception
- commanding
- data processing
- data archiving and distribution
- planning and scheduling



[GlobalImaging, 2009]:

Telemetry includes both information on the status of the spacecraft (housekeeping data) and measurements obtained by the payload.

Ground system (cnt'd)

Telemetry data representation:
- numerical (right)
- graphical (below)

```
Uptime is 226/16:52:39. Time is 1/23/1995 06:56:20
Telemetry data is:
 0 Rx E/F Audio(W):      2.140 V(p-p)     1 Rx E/F Audio(N):      2.165 V(p-p)
 2 Mixer Bias V:         1.346  Volts     3 Osc. Bias V:          0.510 Volts
 4 Rx A Audio (W):       2.140 V(p-p)     5 Rx A Audio (N):       2.140 V(p-p)
 6 Rx A DISC:            0.411    kHz     7 Rx A S meter:        86.000 Counts
 8 Rx E/F DISC:         -0.882    kHz     9 Rx E/F S meter:     116.000 Counts
10 +5 Volt Bus:          4.880  Volts    11 +5V Rx Current:       0.023 Amps
12 +2.5V  VREF:          2.495  Volts    13 8.5V BUS:             8.367 Volts
14 IR Detector:          1.000 Counts    15 LO Monitor I:         0.001 Amps
16 +10V Bus:            10.657  Volts    17 GASFET Bias I:        0.004 Amps
18 Ground REF:           0.000  Volts    19 +Z Array V:           0.205 Volts
20 Rx Temp:              1.814  Deg.C    21 +X (RX) temp:        13.916 Deg.C
22 Bat 1 V:              1.302  Volts    23 Bat 2 V:              1.314 Volts
24 Bat 3 V:              1.304  Volts    25 Bat 4 V:              1.297 Volts
26 Bat 5 V:              1.319  Volts    27 Bat 6 V:              1.315 Volts
28 Bat 7 V:              1.313  Volts    29 Bat 8 V:              1.303 Volts
30 Array V:             10.085  Volts    31 +5V Bus:              4.802 Volts
32 +8.5V Bus:            7.998  Volts    33 +10V Bus:            11.147 Volts
34 BCR Set Point:       20.213 Counts    35 BCR Load Cur:         0.094 Amps
36 +8.5V Bus Cur:        0.027   Amps    37 +5V Bus Cur:          0.251 Amps
38 -X Array Cur:        -0.011   Amps    39 +X Array Cur:        -0.011 Amps
40 -Y Array Cur:        -0.012   Amps    41 +Y Array Cur:        -0.011 Amps
42 -Z Array Cur:        -0.017   Amps    43 +Z Array Cur:        -0.011 Amps
44 Ext Power Cur:       -0.020   Amps    45 BCR Input Cur:        0.213 Amps
46 BCR Output Cur:      -0.017   Amps    47 Bat 1 Temp:           8.470 Deg.C
48 Bat 2 Temp:         -18.760  Deg.C    49 Baseplt Temp:         7.260 Deg.C
50 FM TX#1 RF OUT:       0.026  Watts    51 FM TX#2 RF OUT:      -0.003 Watts
52 PSK TX HPA Temp:    -13.919  Deg.C    53 +Y Array Temp:        4.234 Deg.C
54 RC PSK HPA Temp:     -0.002  Deg.C    55 RC PSK BP Temp:       1.209 Deg.C
56 +Z Array Temp:       -5.448  Deg.C
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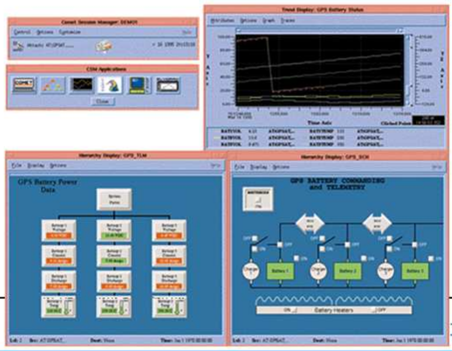


Typically applied (semi) real-time to monitor the status of the satellite, but can also be used to monitor measurements/quality of the payload.

Ground system (cnt'd)

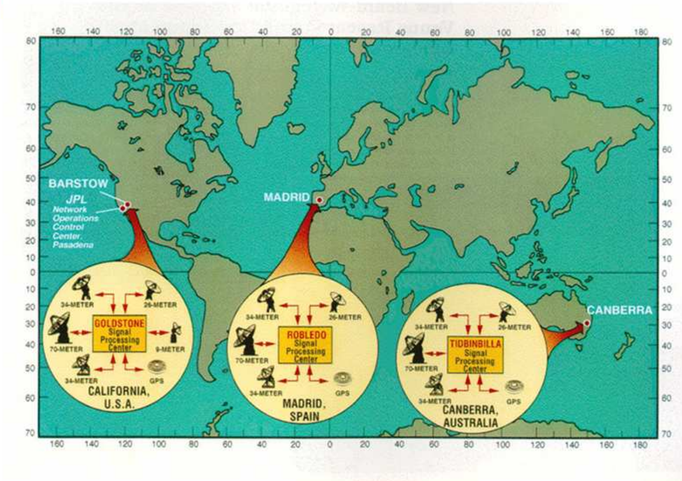
Ground station network: example 1: DORIS

[CNES, 2009]

The French DORIS system (abbreviation for Doppler Orbitography and Radiopositioning Integrated by Satellite) is used for orbit determination of scientific satellites.

Ground system (cnt'd)

Ground station network: example 2: NASA's Deep Space Network (DSN)



[NASA, 2009]

The Deep Space Network is one of the few options for contact with interplanetary spacecraft → overloaded!

Ground system (cnt'd)

Radio communication frequencies

• L-band	1 – 2 GHz
• S-band	2 – 4 GHz
• C-band	4 – 8 GHz
• X-band	8 – 12 GHz
• Ku-band	12 – 18 GHz
• K-band	18 – 26.5 GHz
• Ka-band	26.5 – 40 GHz
• Etc.	

Ground system (cnt'd)

[NASA, 2009]

The (parabolic) antenna is the most prominent (size, cost) element of a ground station.

Its diameter D [m] is related to the distance to the satellite d [km], the carrier frequency f [Hz], the telemetry bitrate b [bits/s] and the satellite transmitter power p [W]:

$$D = \frac{k\, d}{f} \sqrt{\frac{b}{p}}$$

k = const = 6000

Example: satellite at distance of 3000 km, 1 W S-band transmitter (2 GHz), 1 Mbit/s:

$$D = \frac{6 \times 10^3 \; 3000}{2 \times 10^9} \sqrt{\frac{1 \times 10^6}{1}} = 9\, m$$

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This relation holds for communication using radio-waves; k is a constant (6×10^3).

Alternatives for the S-band are the K_a and K_u-band; the use of particular frequencies is coordinated/prescribed by the International Telecommunications Union (ITU).

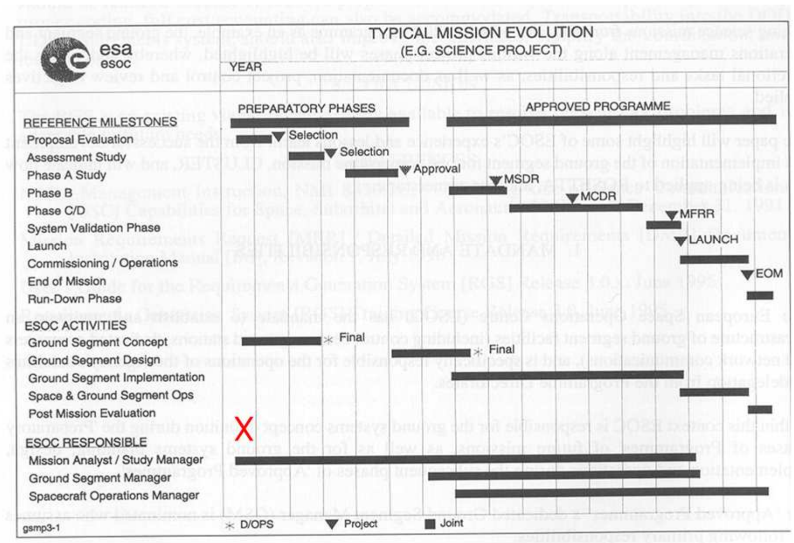
Ground system (cnt'd)

Contact times: exercise

- The (low-rate) instruments of the polar orbiting ENVISAT produce 120 Gbit during a single orbit
- This data is stored on 2 Solid State Recorders
- To dump the stored data, a playback rate of 50 Mbit/sec is used (X-band)
- Compute the required contact time per orbit
- How many ground stations are needed, if a single one can contact the satellite for 9.5 minutes per pass?
- What would be convenient locations for these ground stations?

Ground system (cnt'd)

Design and sizing: when?

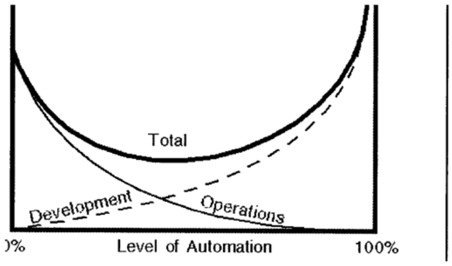


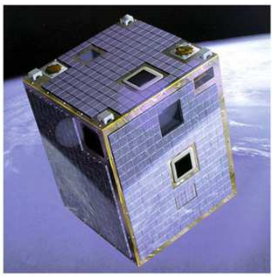
[ESA]

Ground system (cnt'd)

Trends in ground systems:

- Increase in automation and autonomy (reduce costs, be smarter, meet multi-user demands)





- Use expert systems and artificial intelligence

Example:
PROBA-1

Ideally, the level of automation should be selected such that the total cost are minimum, i.e. d(total_cost)/d(level_of_automation) = 0. In reality, the curve for total cost will not be so smooth.

PROPBA-1 is a Belgium mission. Kudo's!

Ground system (cnt'd)

Question 1:

Consider a lander on the Moon (distance 380,000 km), which is to send data packages of 1000 bit/s to Earth at a frequency of 2.6 GHz (i.e. S-Band), and with a transmitting power of 20 W.

a) What is the required diameter for a receiving antenna on Earth?

b) If we have to do this with a receiver dish with 2 m diameter, how would we have to change the emitted power to accomplish the transmission rates?

Answers: see footnotes **(BUT TRY YOURSELF FIRST!!)**

Answers:

a) D = 6.2 m

b) P = 192.2 W

Ground system (cnt'd)

Question 2:

Consider the situation that the development costs of a new ESA mission are given as DC = $0.001 \times A^2$ (where A is the percentage of automation), and the operational costs are given by OC = (15+25/A); both DC and OC are in million euro's.
What would be the best level of automation, and what would be the corresponding total cost?

Answer: see footnotes **(BUT TRY YOURSELF FIRST!!)**

Answers: A = 23.21%, DC = 0.53 M€, OC = 16.08 M€.

Operations

Scope:

All activities related to
- planning
- preparation
- execution
- evaluation

of the control of the space and ground segments during the operational phase of a space mission

Ground segment = hardware, facilities
Operations = use of ground segment (& satellite) -> activities

Operations (cnt'd)

Question:

What percentage of total life cycle cost (LCC) does mission operations typically cost?

a) < 5 %
b) 5 – 10 %
c) 10 – 25 %
d) 25 – 50 %
e) > 50 %

????

Operations (cnt'd)

Statistics on existing missions:

type	*mission*	*Op. cost [% LCC]*
traditional	ENVISAT	13
	Cassini-Huygens	25
faster-better-cheaper	Freja	3
	Genesis	18
	Stardust	17
	Lunar Prospector	45
	NEAR	24
	Mars Express	31
	Mars Pathfinder	7
	Mars Surveyor	20
	Mars Odyssey	27
technology pioneer	Deep Space I	7
	Clementine	6

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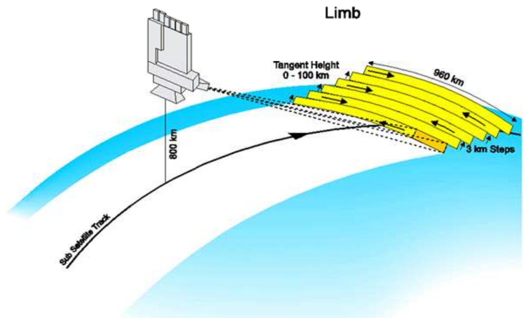
So…. No consistent answer! "LCC" is abbreviation for Life Cycle Cost (i.e. the full cost of a mission, covering all expenses).

Operations (cnt'd)

Example mission operation concept: SCIAMACHY (earth observation instrument on board of ENVISAT):



[DLR, 2009]

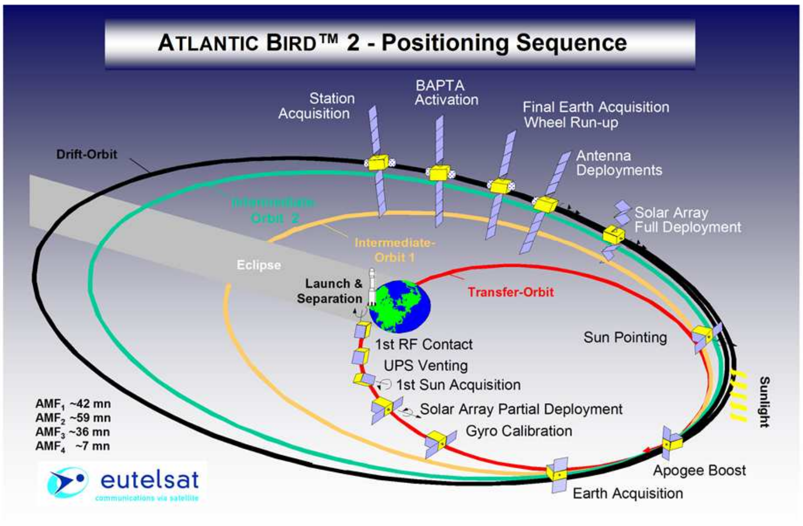
Options for scanning:

- rotate entire vehicle
- rotate instrument
- rotate mirror inside instrument
- …..

Designing is not only "inventing" the instrument, but also describing how it is to be used!

Operations (cnt'd)

Example sequence of mission events: deployment of Atlantic Bird 2:



AMF = Apogee Motor Firing

RF = Radio Frequency

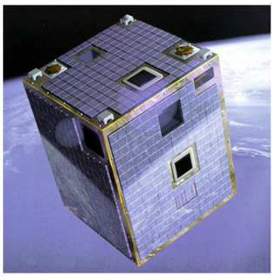
UPS = Unified Propulsion System

BAPTA = Bearing And Power Transmission Assembly

Operations (cnt'd)

Trends, challenges:

- higher autonomy onboard and on ground (PROBA – Project for On-Board Autonomy)
- onboard data storage
- onboard data processing
- higher data rates
- access ground data storage
- fast ground data processing
- flexibility satellite firms



[SpaceApplications, 2009]

Operations (cnt'd)

Questions

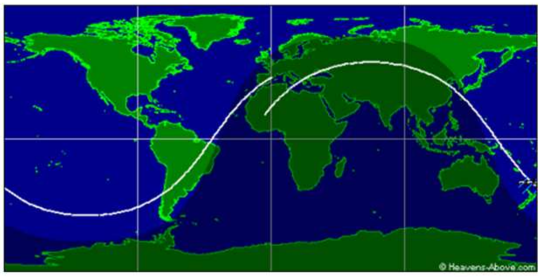
1. Describe the sequence of activities that take place during the launch of a vehicle (until deployment in orbit)
2. Describe the sequence of activities that take place during the launch of a vehicle (until deployment in orbit)
3. Mention at least 5 trends in operations, and describe each one briefly (1-2 lines each)

ANSWER: FOOTNOTE BELOW **(BUT TRY YOURSELF FIRST!!)**

Answers (**DID YOU TRY?)**

1. Assembly of launcher – integration with payload – testing while on launch pad – ignition – burnout and jettison of stages – jetison of payload shroud – deltaV to arrive in parking orbit – deployment of solar panels and pointing towards Sun – deployment of antennas and contact with ground stations - checkout of instruments
2. See sheet 43.
3. See sheet 44.

Ground track and visibility



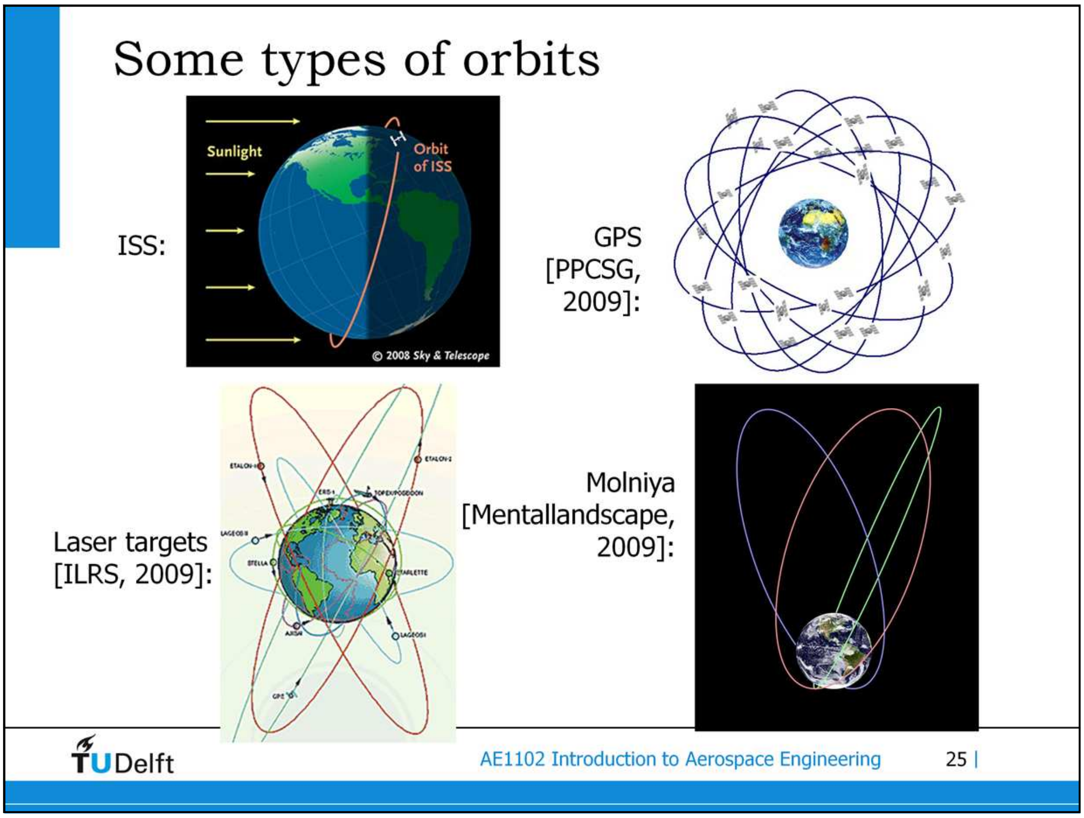
Ground track?
- pattern of vertical projections of satellite position on Earth surface.

Shape? Driven by:
- orbit inclination
- orbital period + rotation Earth

Visibility?
- direct link between spacecraft and/or target (including geometry)

Why?
- fulfilling mission objective(s)
- downloading measurements
- uploading commands

Mission objectives can be as broad as observing a certain surface area (crop monitoring, fire detection, intelligence), navigation (GPS, Galileo, …), etcetera.



ISS = International Space Station; GPS = Global Positioning System; ILRS = International Laser Ranging Service (satellites depicted are equipped with laser retroreflectors to obtain distance measurements with accuracies of a few mm)

Ground track and visibility (cnt'd)

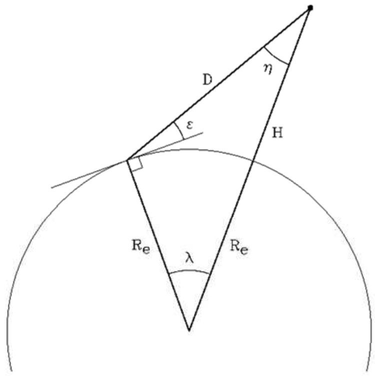
Ground track:

- The point where the position vector of the satellite crosses the Earth's surface is called the sub-satellite point
- The trace of successive sub-satellite points is the ground track
- During one orbital revolution the ground track describes a sine-like shape
- The maximum latitude is equal to the inclination (or 180° – i)
- The ground track is shifted westward by $\Delta\Lambda = 15 \times T$ ($\Delta\Lambda$ in °, T is orbital period in hrs)
- LEO: $\Delta\Lambda \sim 23°$
- Direct contact possible when the satellite is within the visibility circle around a station/target
- Size of visibility circle depends on satellite altitude and minimum elevation.

Ground track and visibility (cnt'd)

2-dimensional geometry:

- D – distance between satellite and point on Earth (station, target) [km]
- h – altitude orbit [km]
- ε – elevation of satellite above horizon [°]
- λ – Earth central angle between target and satellite [°]
- η – satellite-centered angle between Earth center and target [°]



relations: sin rule, cos rule, Σ(angles) = 180°

e.g. H, ε known ➔ λ, η, D

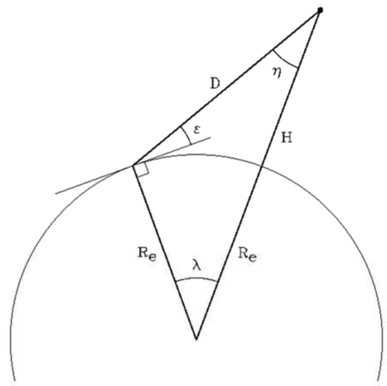
or H, η known ➔ λ, ε, D

Arbitrary triangle with sides a, b and c, and angles α, β and γ (opposite to sides a, b and c, respectively). Sine rule: sin α / a = sin β / b = sin γ / c. Cosine rule: $c^2 = a^2 + b^2 - 2\ a\ b \cos \gamma$ (similar expressions for a^2 and b^2). In an arbitrary triangle, any set of 3 known parameters can be used to derive the other 3 parameters. In computations, it is sometimes handy to first derive another parameter (angle, side) before computing the final, desired parameter.

Ground track and visibility (cnt’d)

Example 1:

- consider ENVISAT (h = 780 km, minimum ground elevation 20°):
- question: what is the maximum distance D?
- solution:



$$\frac{\sin(90+\varepsilon)}{R_e+H} = \frac{\sin\eta}{R_e} \quad \Rightarrow \quad \eta = 56.86°$$

$$(90+\varepsilon)+\lambda+\eta = 180 \quad \Rightarrow \quad \lambda = 13.14°$$

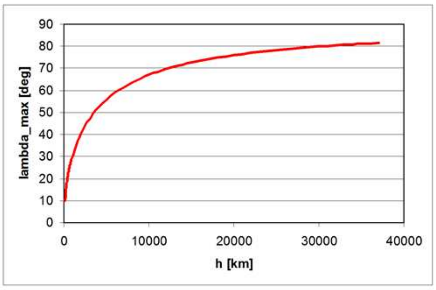
$$\frac{\sin\lambda}{D} = \frac{\sin(90+\varepsilon)}{R_e+H} \quad \Rightarrow \quad D = 1731.7\ km$$

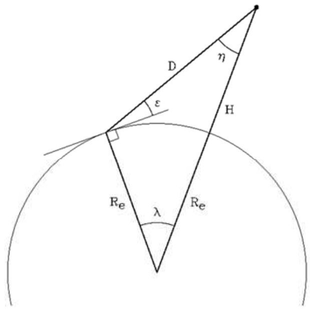
R_e = 6378.137 km

Ground track and visibility (cnt'd)

Example 2:

- maximum value of Earth-central angle λ is obtained for minimum value for elevation ε (i.e. 0°).
- λ_{max} f(h)?
- answer:





Ground track and visibility (cnt'd)

QUESTION:

Maximum elevation of a satellite in a circular orbit around the Earth as seen from a ground station?

- Assume a satellite at 800 km altitude above the Earth with inclination = 50°
- Assume a ground station at 52° north latitude
- What is the maximum elevation of the satellite?

- Assume a satellite at 3000 km altitude above the Earth with inclination = 50°
- Assume a ground station at 60° south latitude
- What is the maximum elevation of the satellite?

See notes for answers

NB: By now you should know the relevant Earth parameters

Satellite at 800 km, 50 deg incl, station at 50 deg latitude: elevation = 72.523 deg

Satellite at 3000 km, 50 deg incl, station at -60 deg latitude: elevation = 60.322 deg

Ground track and visibility (cnt'd)

QUESTION:

Maximum contact time for a satellite in circular orbit around the Earth (simplified example; NO Earth rotation; Zenith pass)

- Assume a satellite at 800 km altitude above the Earth
- How long is the maximum contact time (in minutes)?
- How long is the contact time if the minimum elevation is 20 degrees?

- Assume a satellite at 3000 km altitude above the Earth
- How long is the maximum contact time (in minutes)?
- How long is the contact time if the minimum elevation is 20 degrees?

See notes for answers

NB: By now you should know the relevant Earth parameters

HINT: First use the cosine rule to create a quadratic equation from which you can compute the distance between the ground station and the satellite

Satellite at 800 km:

Max contact time: Elevation = 0 → Tvis = 15.3 min

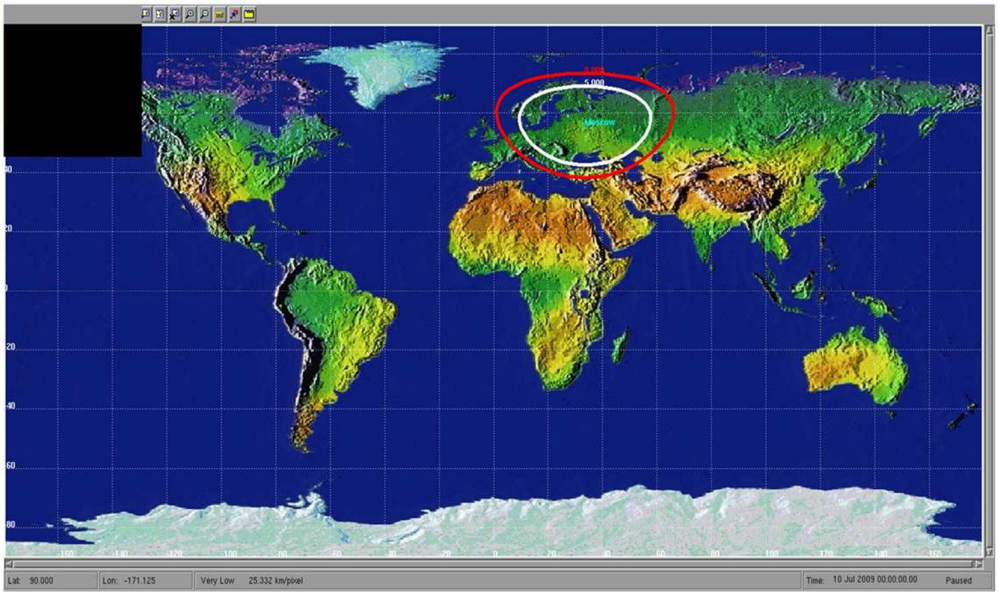
Elevation = 20 → Tvis = 7.5 min

Satellite at 3000 km:

Max contact time: Elevation = 0 → Tvis = 39.5 min

Elevation = 20 → Tvis = 25.3 min

Ground track and visibility (cnt'd)

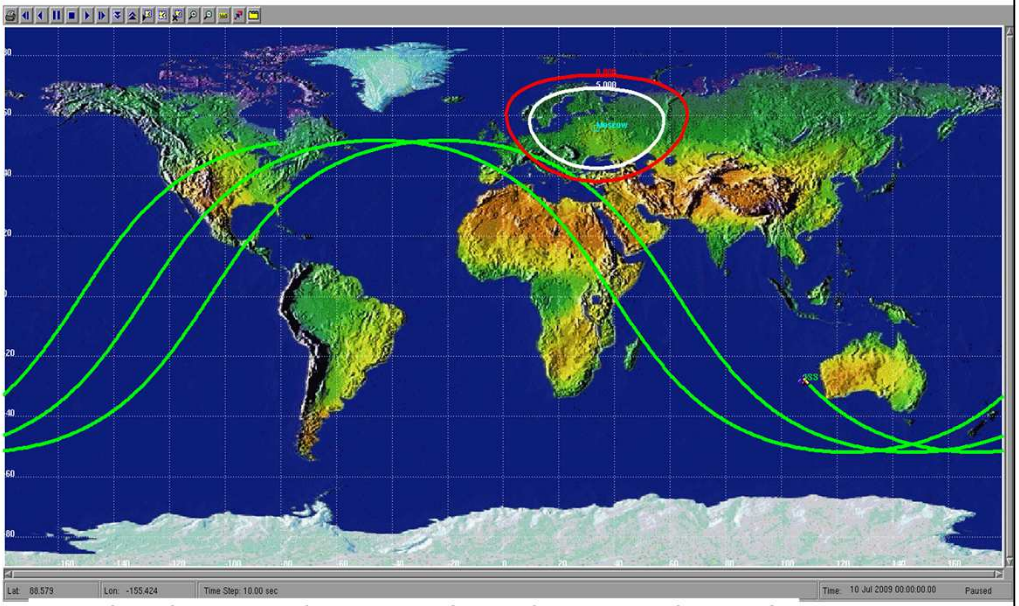


Visibility contours Moscow (ε=0° (red) and ε=5° (white))

The visibility circles hold for an object at the altitude of the International Space Station (335 km). They deform because of the projection of the map; on a perfectly round sphere it would be a true circle.

Picture generated with Satellite Tool Kit (STK).

Ground track and visibility (cnt'd)

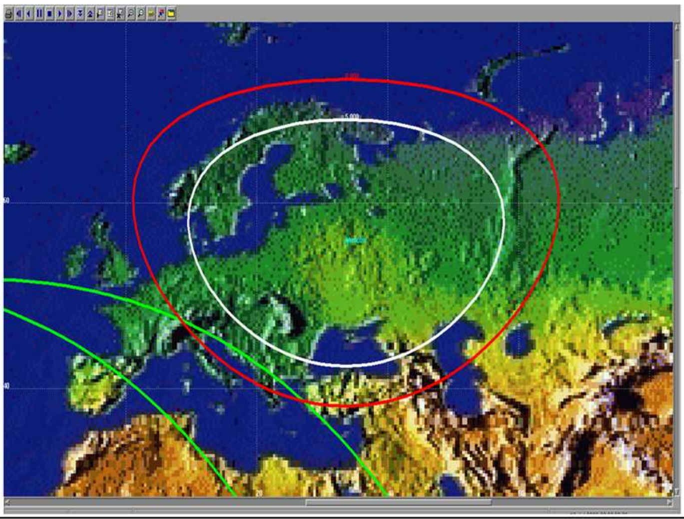


Ground track ISS on July 10, 2009 (00.00 hrs – 04.00 hrs UTC)

The ISS moves from west (left) to East (right). The simulation covers about 2.5 orbital revolutions. Picture generated with Satellite Tool Kit (STK).

Ground track and visibility (cnt'd)

- 1st track: contact during 160 seconds, ε_{max} = 3.2°
- 2nd track: shifted 23.2° to the west, no contact



Zooming in. Picture generated with Satellite Tool Kit (STK).

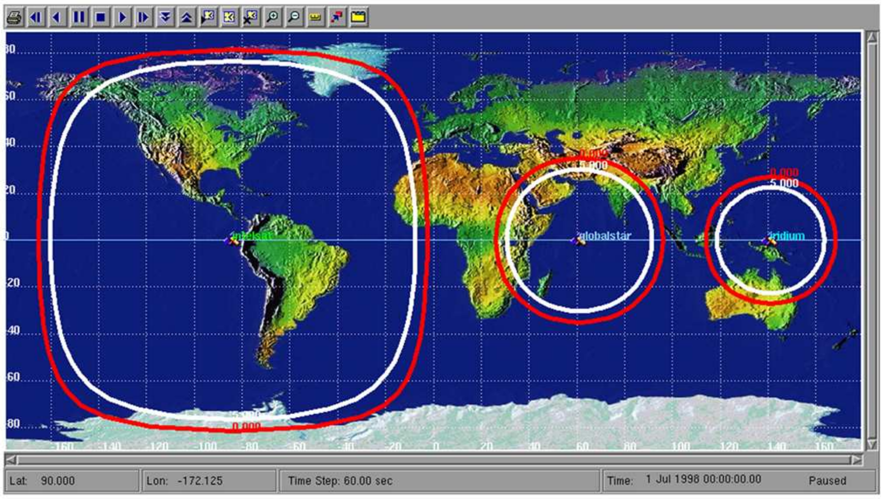
Communication

- General purpose: transfer information from 1 point (satellite?) to another (ground station?)
- Options satellite communication: LEO, GEO

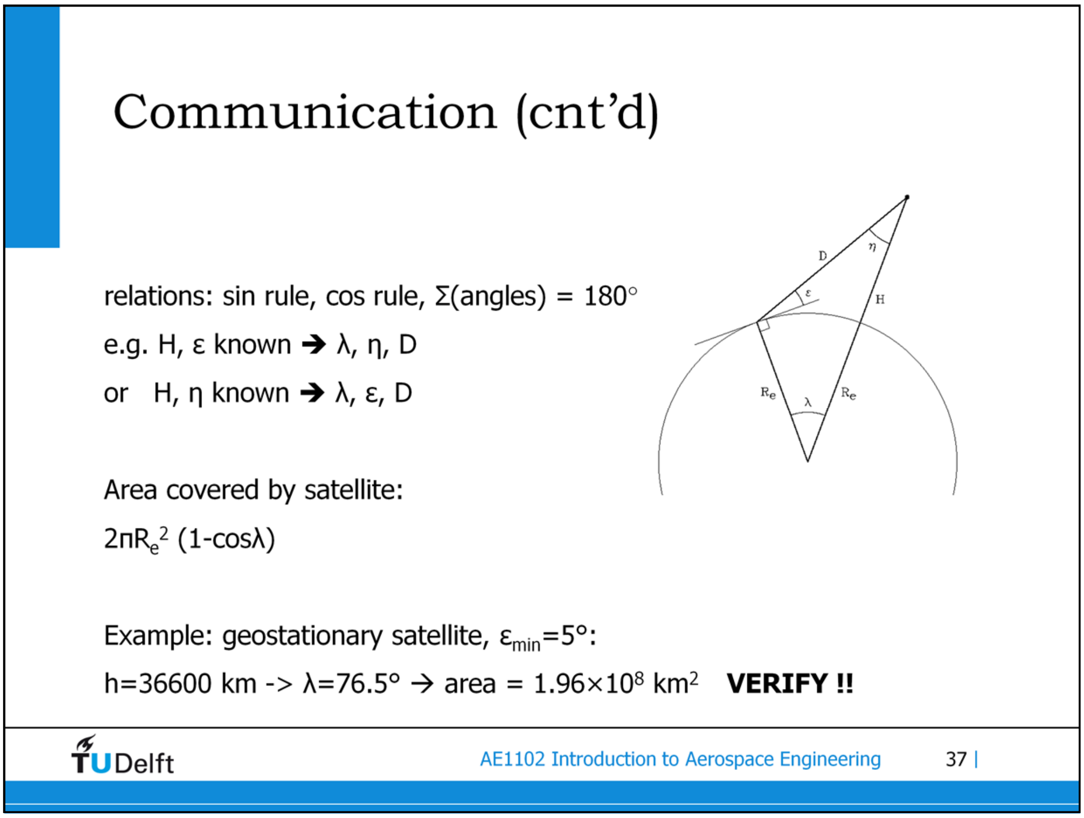
orbit	*advantage*	*disadvantage*
LEO	short distance -> small delay	small coverage -> many satellites
		satellite motion
		new technology
GEO	large coverage -> 3 sats enough	large distance -> delay
	stationary -> simple receivers	
	long lifetime	
	proven technology	
	large capacity	

Communication (cnt'd)

Earth coverage: GEO (Intelsat, left) vs LEO (Globalstar and Iridium, right):



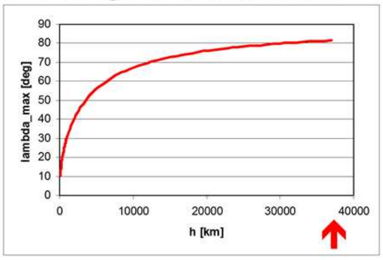
Picture generated with Satellite Tool Kit (STK). The LEO satellites Globalstar and Iridium are not necessarily located above the equator.

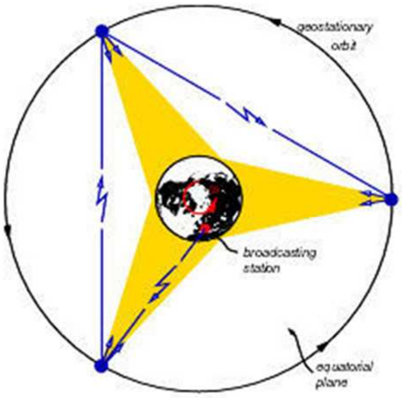


Arbitrary triangle with sides a, b and c, and angles α, β and γ (opposite to sides a, b and c, respectively). Sine rule: sin α / a = sin β / b = sin γ / c. Cosine rule: $c^2 = a^2 + b^2 - 2\,a\,b\cos\gamma$ (similar expressions for a^2 and b^2). In an arbitrary triangle, any set of 3 known parameters can be used to derive the other 3 parameters. In computations, it is sometimes handy to first derive another parameter (angle, side) before computing the final, desired parameter.

Communication (cnt'd)

Earth coverage of GEO satellites:





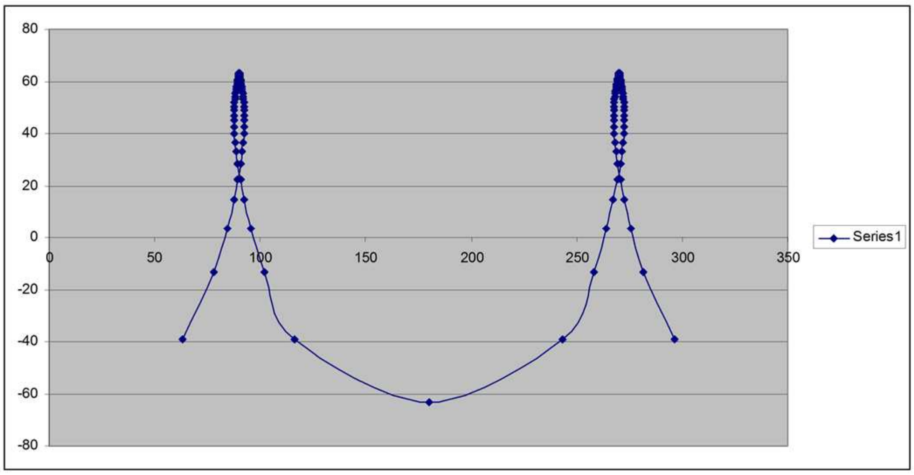
- Stationary, so contact or not
- 3 satellites can cover full Earth
  - geosynchronous satellite proposed by Herman Noordung (1928)
  - communication system proposed by Arthur C. Clarke (1945)

Communication: another solution

MOLNYA system (for communication at high latitudes)

- Two or three satellites in highly eccentric orbits
- 12-hour orbits
- Perigee height ~ 550 km
- Apogee height ~ 40000 km
- Eccentricity ~ 0.74
- Inclination ~ 63.4 degrees
- Perigee in southern hemisphere (short stay)
- Apogee in northern hemisphere (long stay)

Communication: another solution



Ground track of MOLNYA orbit at 10 min intervals

Communication (cnt'd)

Received energy:

$$E = P \frac{A}{4 \pi r^2}$$

E = energy received [W]
P = transmitted energy [W]
r = distance between transmitter and receiver [m]
A = surface area of receiver antenna [m^2]

Communication (cnt'd)

Example energy equation:

1. Communication satellite in LEO (800 km), emitted power 100 W, diameter receiver antenna 10 m: E = 9.7×10^{-10} W

2. Communication satellite in GEO (35800 km), emitted power 100 W, diameter receiver antenna 10 m: E = 4.8×10^{-13} W

3. Idem, diameter receiver antenna 1 m: E = 4.8×10^{-15} W

Note: all situations hold for nadir pointing (i.e. at sub-satellite point)
So: what do we do wrong?

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The receiver antenna with a dish diameter of 1 meter is to be considered as representative for Direct-To-Home (DTH) broadcasting.

Communication (cnt'd)

Question:

Consider a LEO communication system, with satellites in a circular orbit at an altitude of 600 km.

a) If the objective of this system is to provide truly global coverage, what would be the desired inclination of the satellite orbits?

b) Provided that the minimum elevation is 5°, what is the area on the surface of the Earth that can be covered by a single satellite?

c) Provided that there is no overlap between the coverage areas of individual satellites, how many would be needed to cover the entire Earth?

Answers: see footnotes **(BUT TRY YOURSELF FIRST !!)**

Answers:

a) $i = 90°$

b) Area = 14.54×10^6 km^2

c) $N_{sat} = 36$