The ladybird guides

Book II

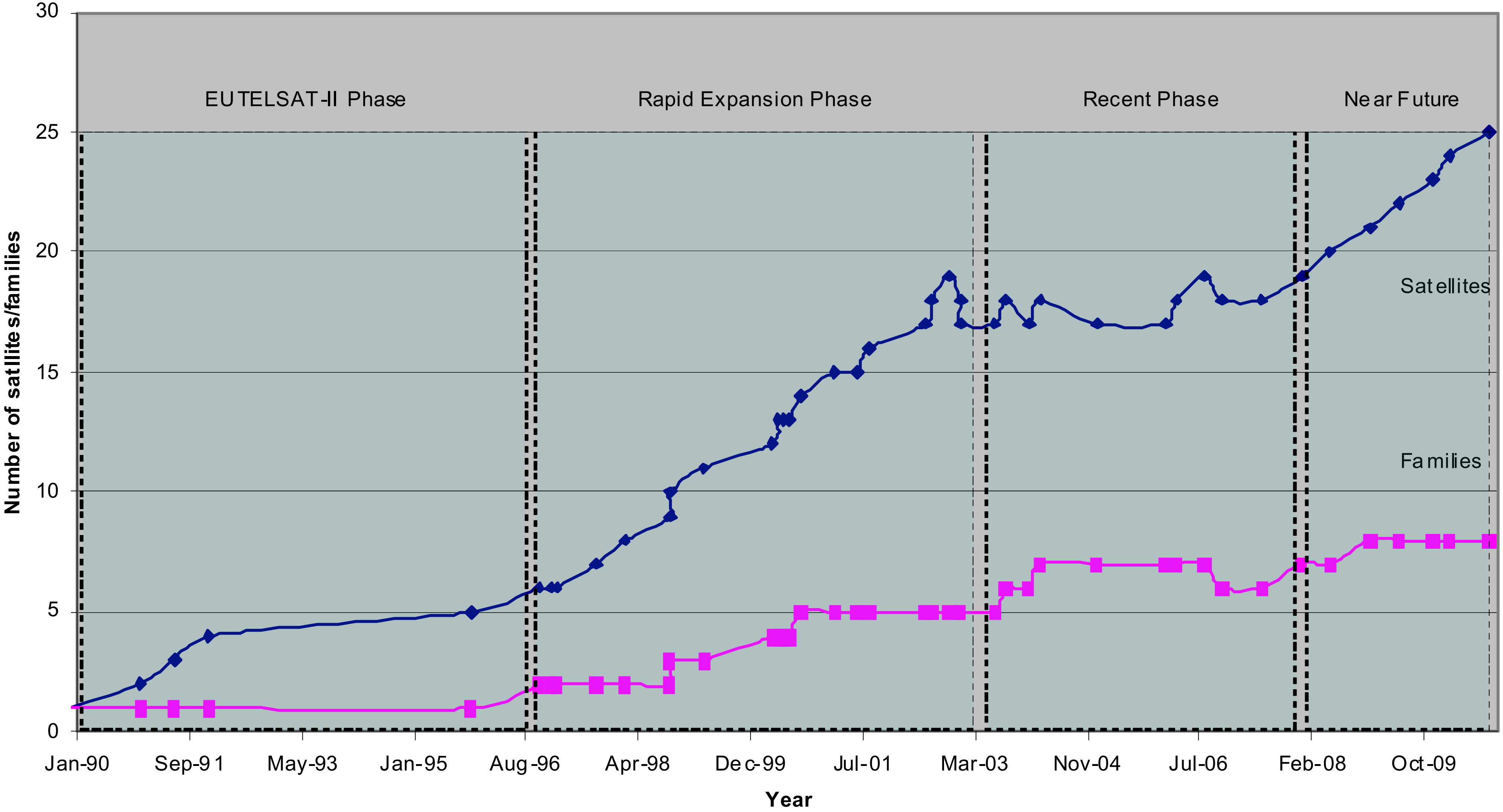
Communicating with your spacecraft

Day 1: The challenge

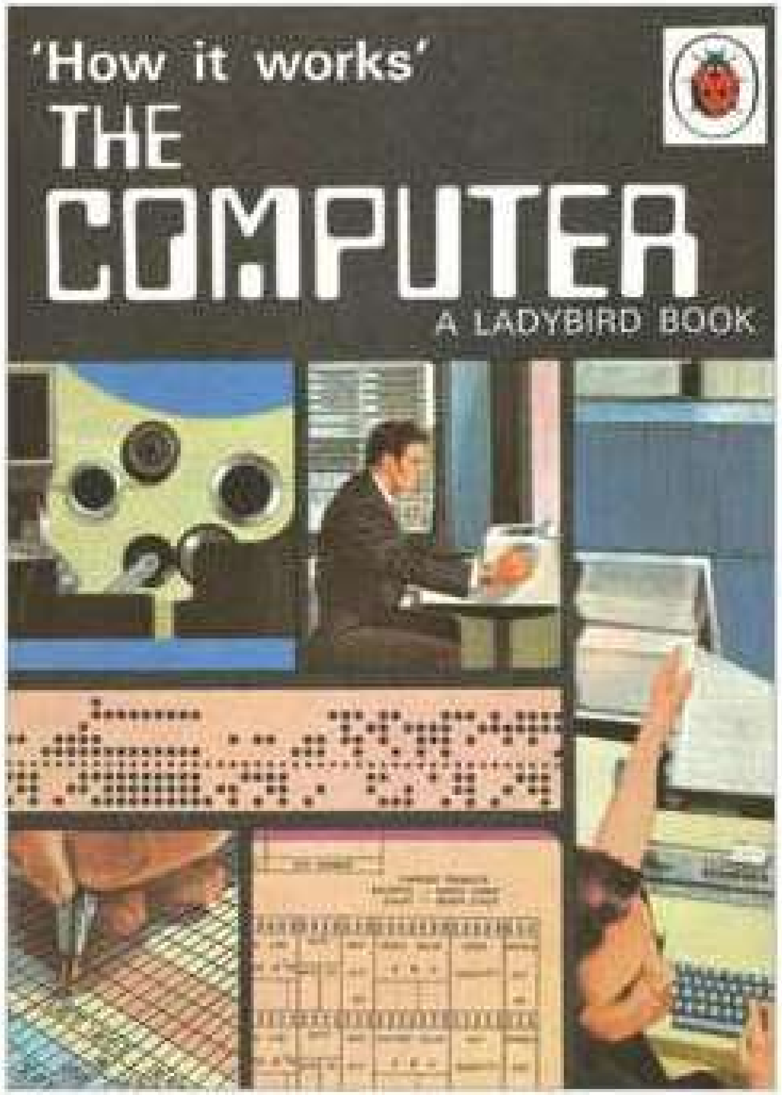
Objective:
To appreciate the scale of the problems that must be overcome

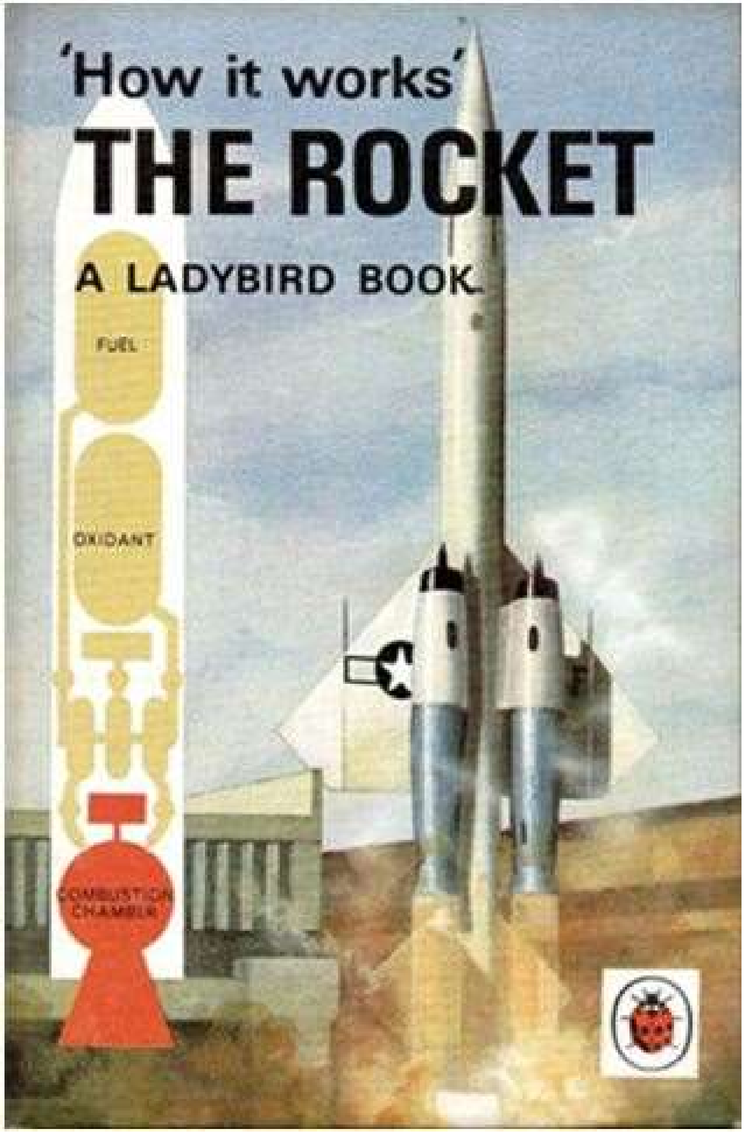
1. Introduction
2. What happens between transmitter and the receiver
3. The characteristics of spacecraft transmitters and receivers
4. You are not alone (other transmitters & receivers)

The Ladybird Guide Story

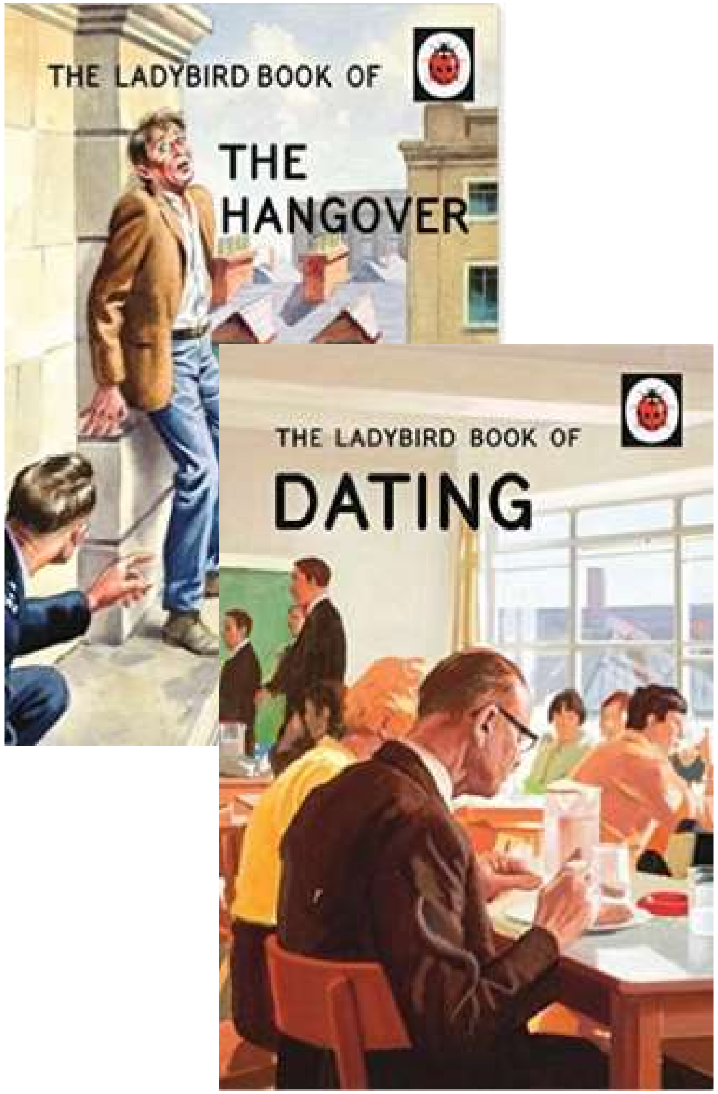


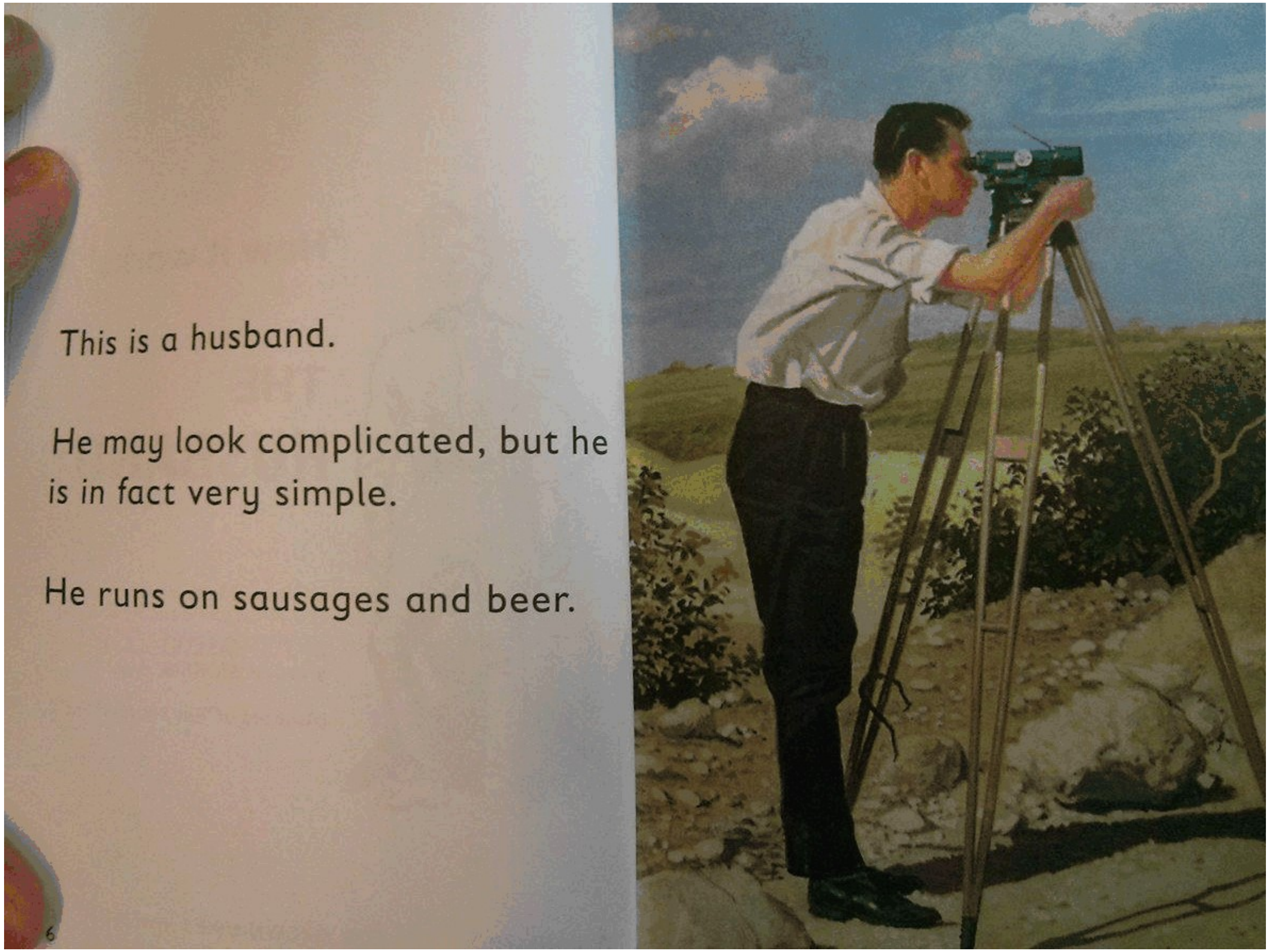
The Original Ladybird Guides





The New Ladybird Guides





My Ladybird Take on Spacecraft

There are different types of missions and spacecraft designs. It can seem confusing!

But remember:

- **Every mission has common problems to solve**
- **Each subsystem design is <u>one</u> solution to a <u>common</u> problem**

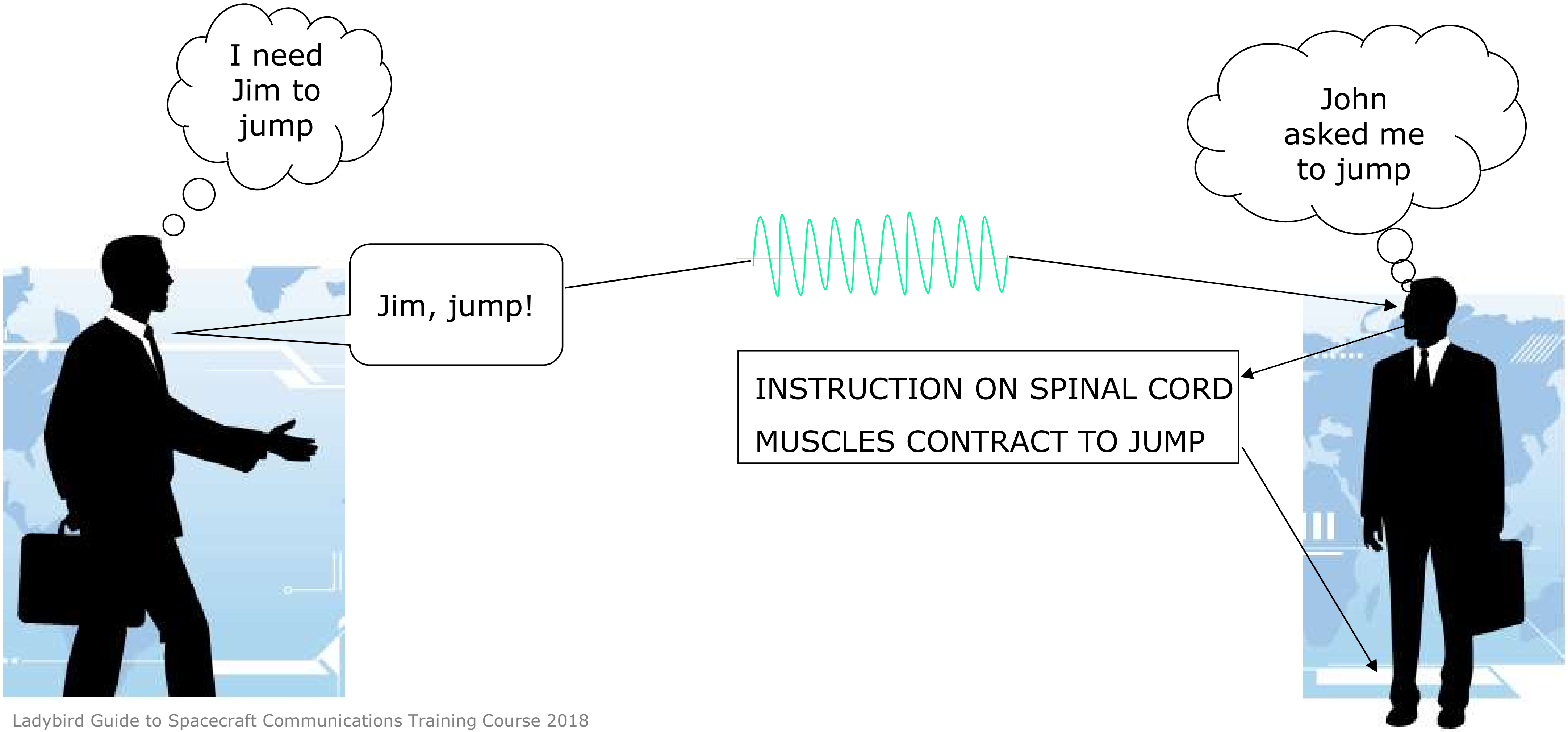
Try to understand the problems <u>before</u> the solutions

Each spacecraft manufacturer will try and differentiate himself from his competitors.
So it is no surprise that these commonalties are not explicit in user manuals.

It is up to you, the operator, to identify and understand the problems from first principles
The Ladybird Guide is a way to help you with this……..

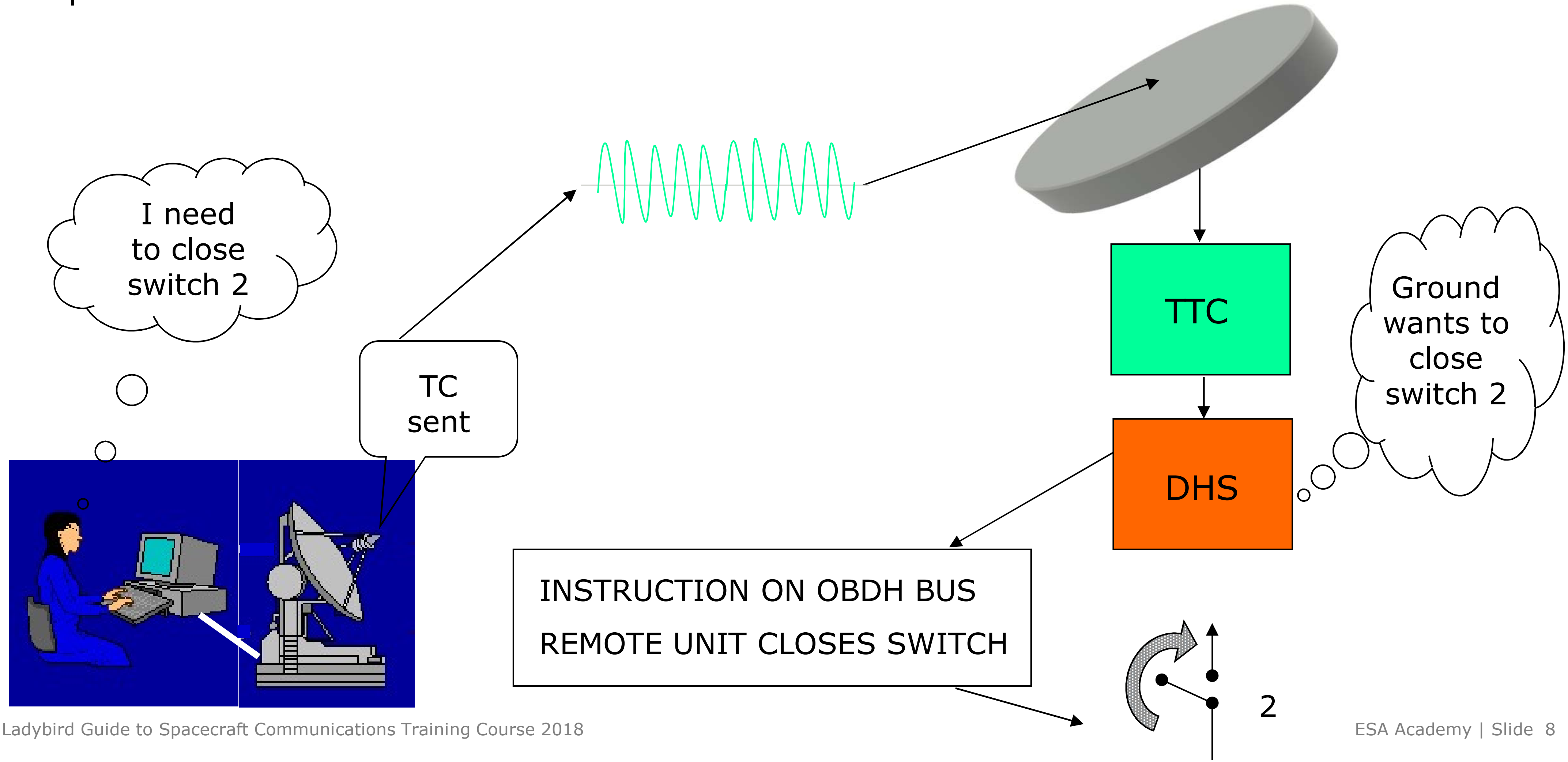
The problem - instructions

Let’s consider all the processes that have to occur when giving someone an instruction. John needs Jim to jump…



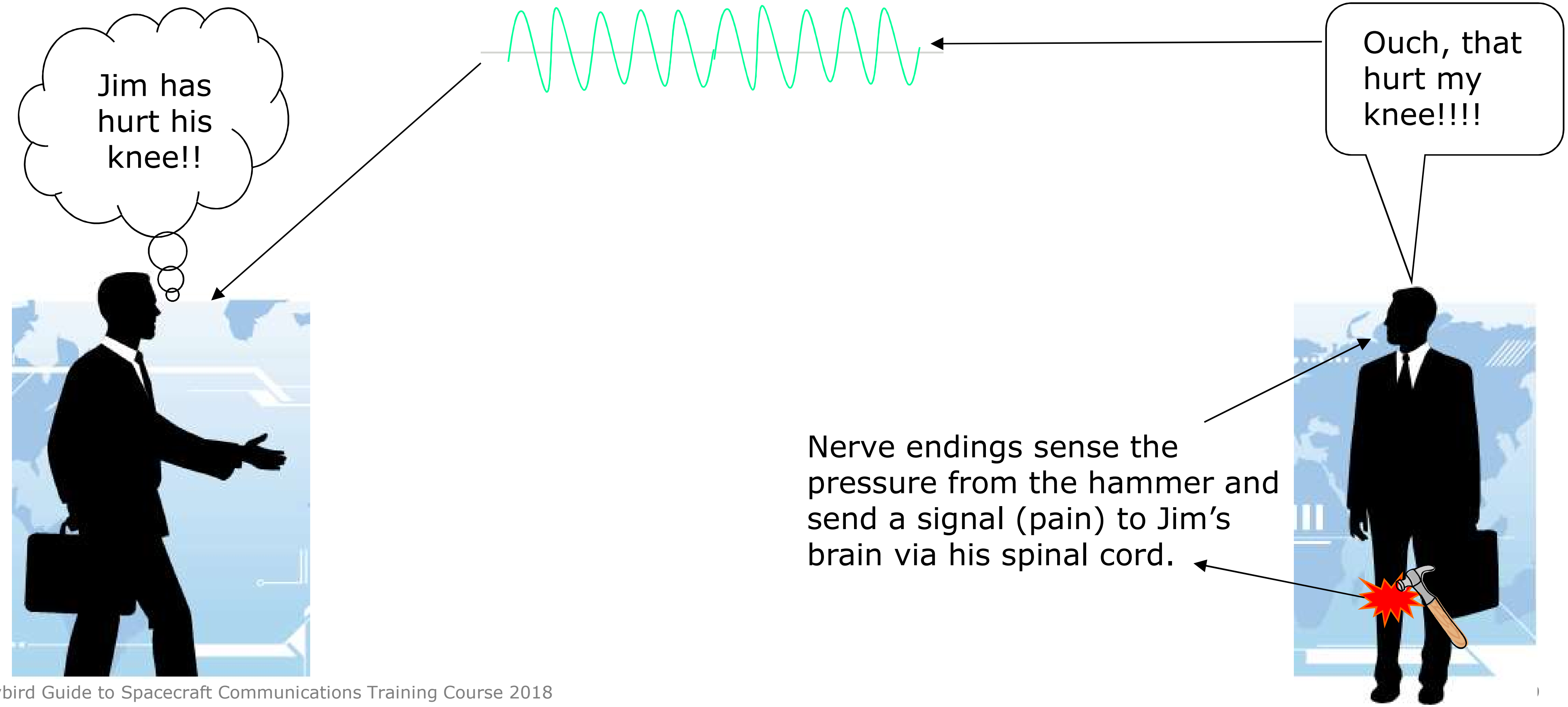
Spacecraft Commanding

Well sending an instruction to a satellite is similar except the ground station acts like a mouth and the TTC antenna/receiver as an ear. The central processor on-board is the satellite's brain.



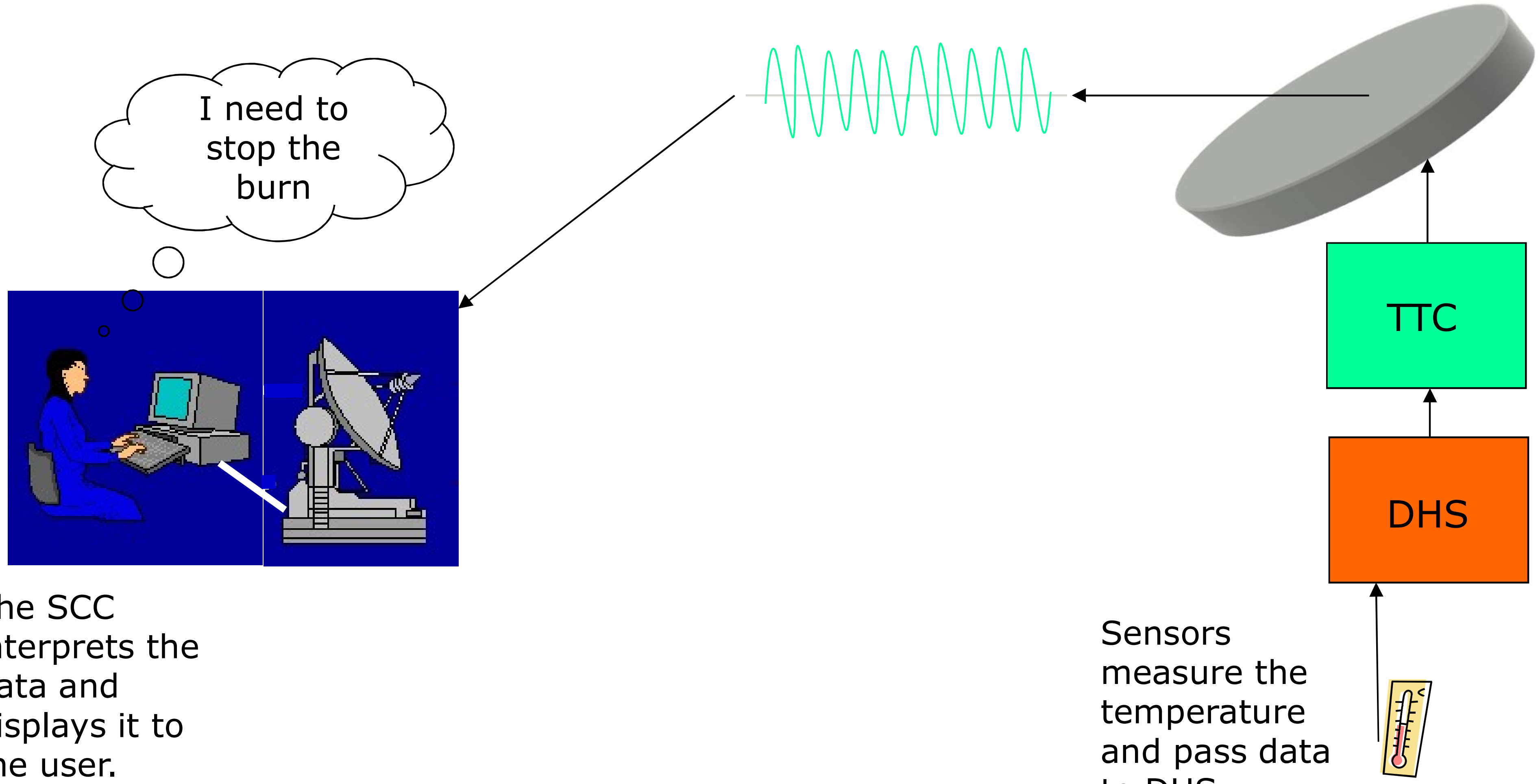
The problem – health and status

Now let's consider receiving information about the state (or health) of another person… . How does Jim react when he drops the hammer?



Spacecraft Telemetry

Monitoring the state of a satellite is similar except the ground station now acts as an ear and the TTC antenna/transmitter as mouth.

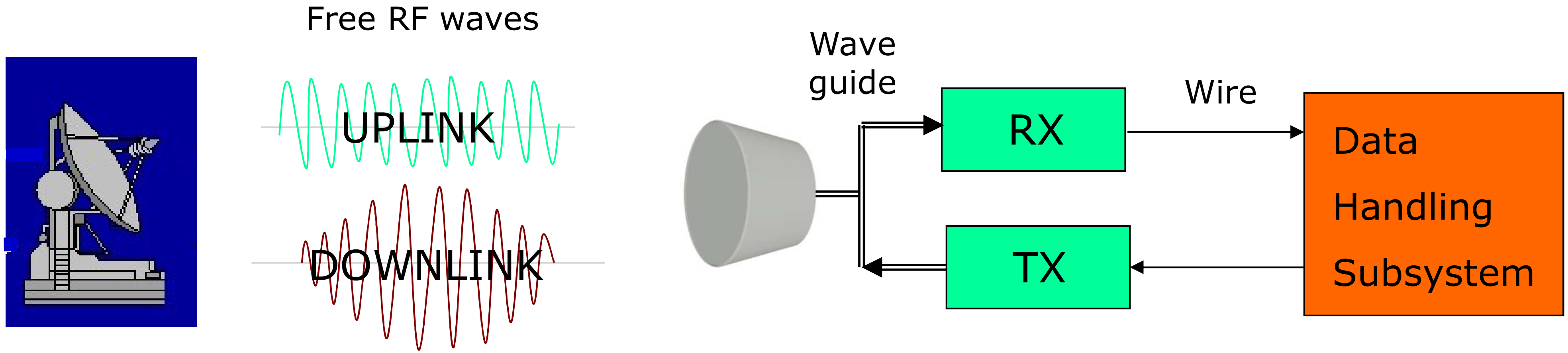


The SCC interprets the data and displays it to the user.

Sensors measure the temperature and pass data to DHS

The classic TT&C lecture

Basic Subsystem Diagram



The station transmits a RF wave on which the controller's instructions (telecommands) are encoded called the *uplink*. The antenna collects this wave and passes it to the receiver which converts this radio wave into a voltage wave and passes this onto the DHS subsystem where it is decoded.

At the same time the DHS passes a voltage wave to the transmitter on which spacecraft information has been encoded. It converts this into a radio wave called the *downlink* and transmits it through the antenna to the station.

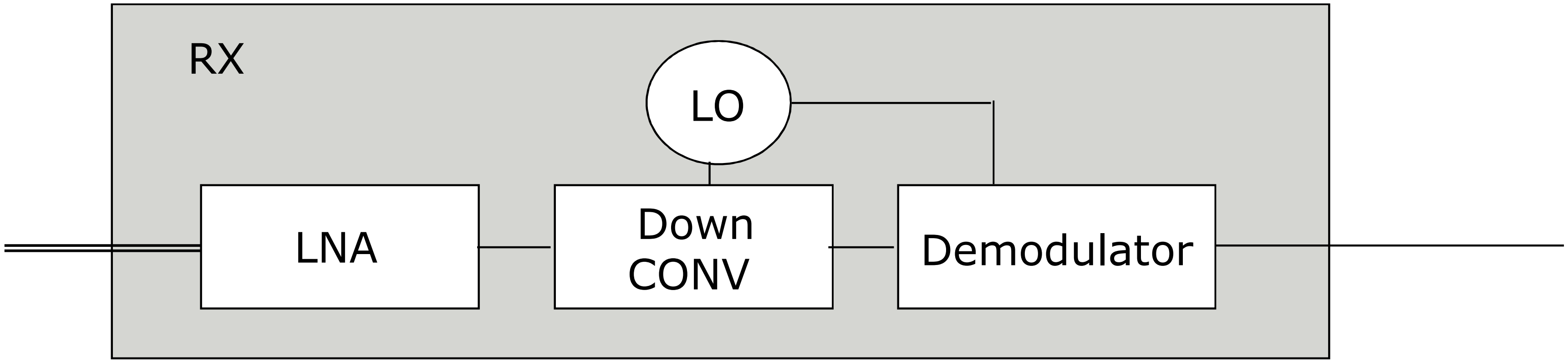
Antenna Types

- Low Gain Antennas
  - Coverage of ½ sphere
  - Gain -3dB to 3 dB
- Isoflux Antennas
  - Coverage of Earth with increase at low elevations
  - Gain X-band about 6 dBi (lower gain in S-band due to size limit)
- Medium Gain Antennas MGA)
  - Mild directional coverage
  - Simple construction, 1-3 m in diameter
  - Gain (S or X-band) 15 dBi to 20 dBi
- High Gain Antennas (HGA)
  - Parabolic dish, 1-3 m in diameter
  - Gain (X-band) 30 to 45 dBi

What is a TTC receiver?

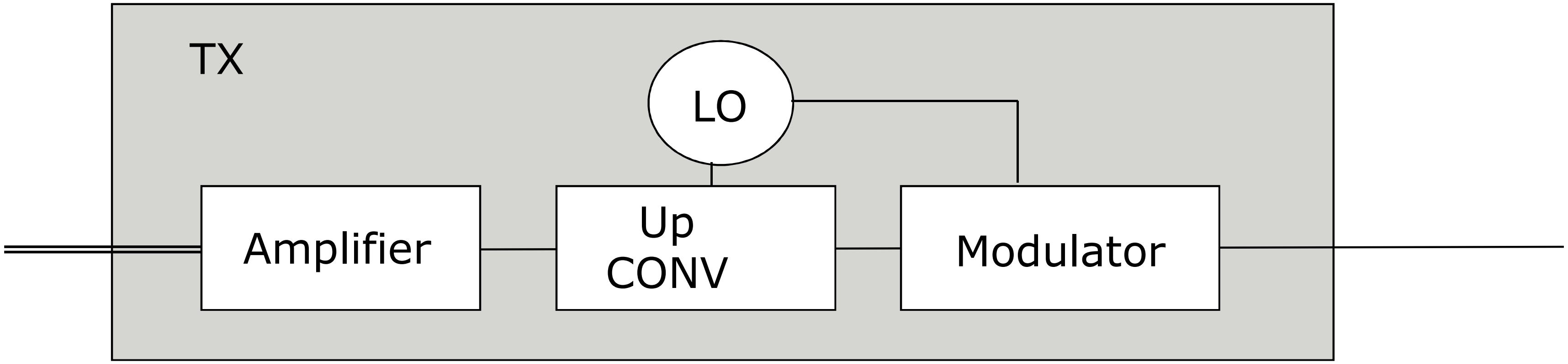
TTC receivers convert the incoming RF wave into a voltage signal.

They contain
1. a low noise amplifier
2. a frequency down converter and associated oscillator
3. a demodulation unit



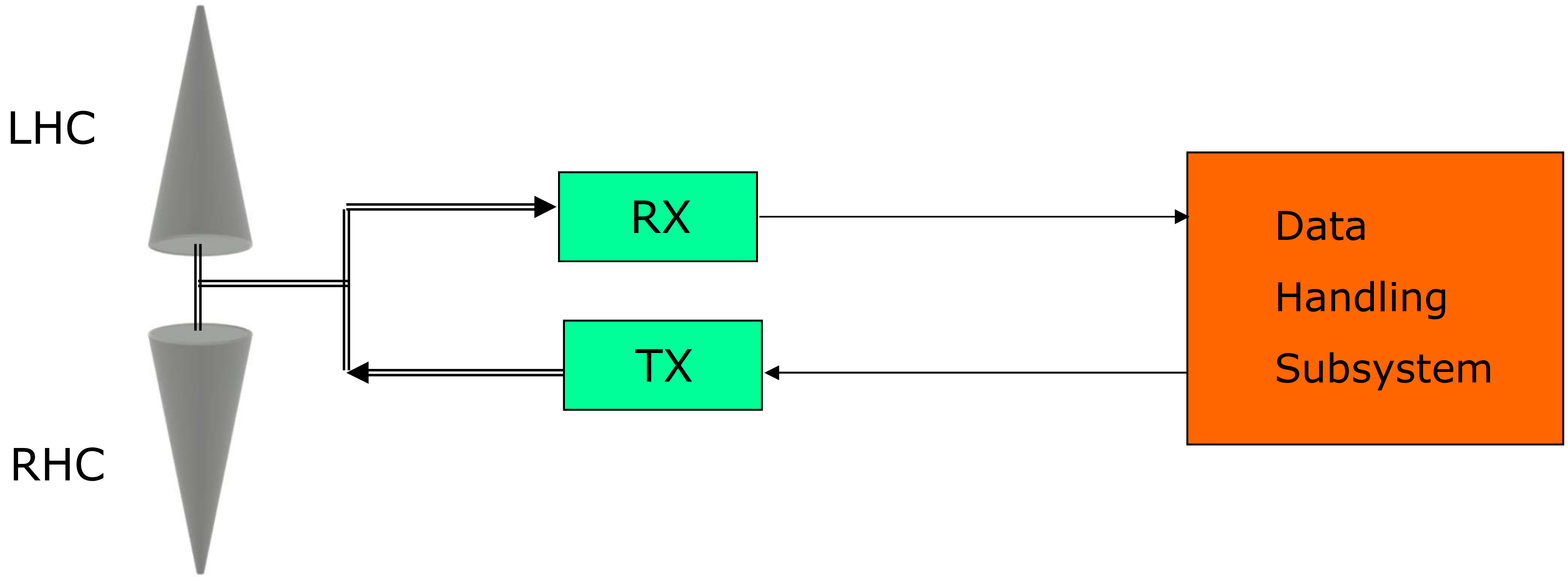
What is a TTC transmitter?

The opposite of a TTC receiver



LEOP set up

Most LEOP ground stations work in S-band so *usually* a TTC system that works in this frequency with full antenna coverage is essential.



Two LGAs are used in LEOP to provide full coverage. They work with opposite polarizations to avoid interfering with each other.

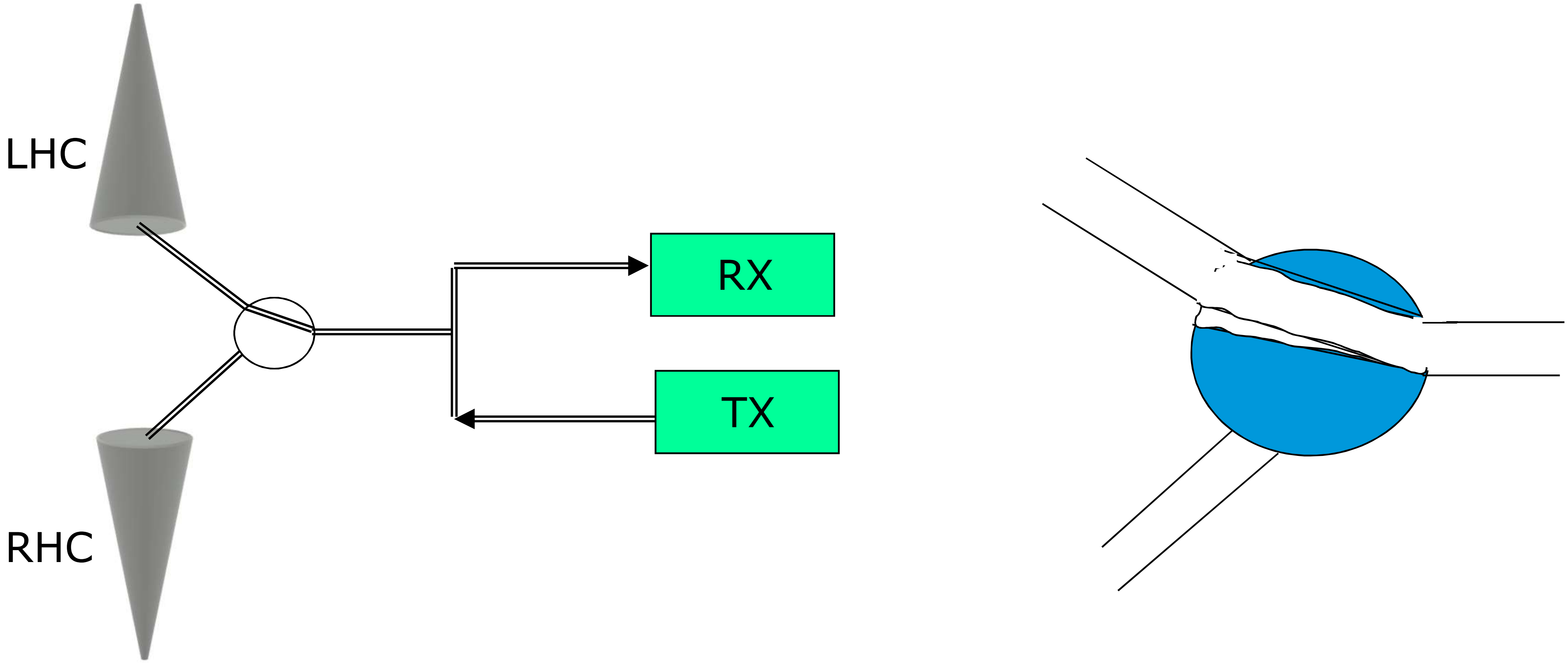
If a RX and TX are placed in the same box, it is referred to as a *transponder*.

Operational Experience: XMM rescue

18 October 2008: XMM AOS and no signal

+2 days: Optical Telescope sightings show XMM is not spinning

+3 days: New Norcia (35m) detects faint telemetry signal but cannot demodulate it



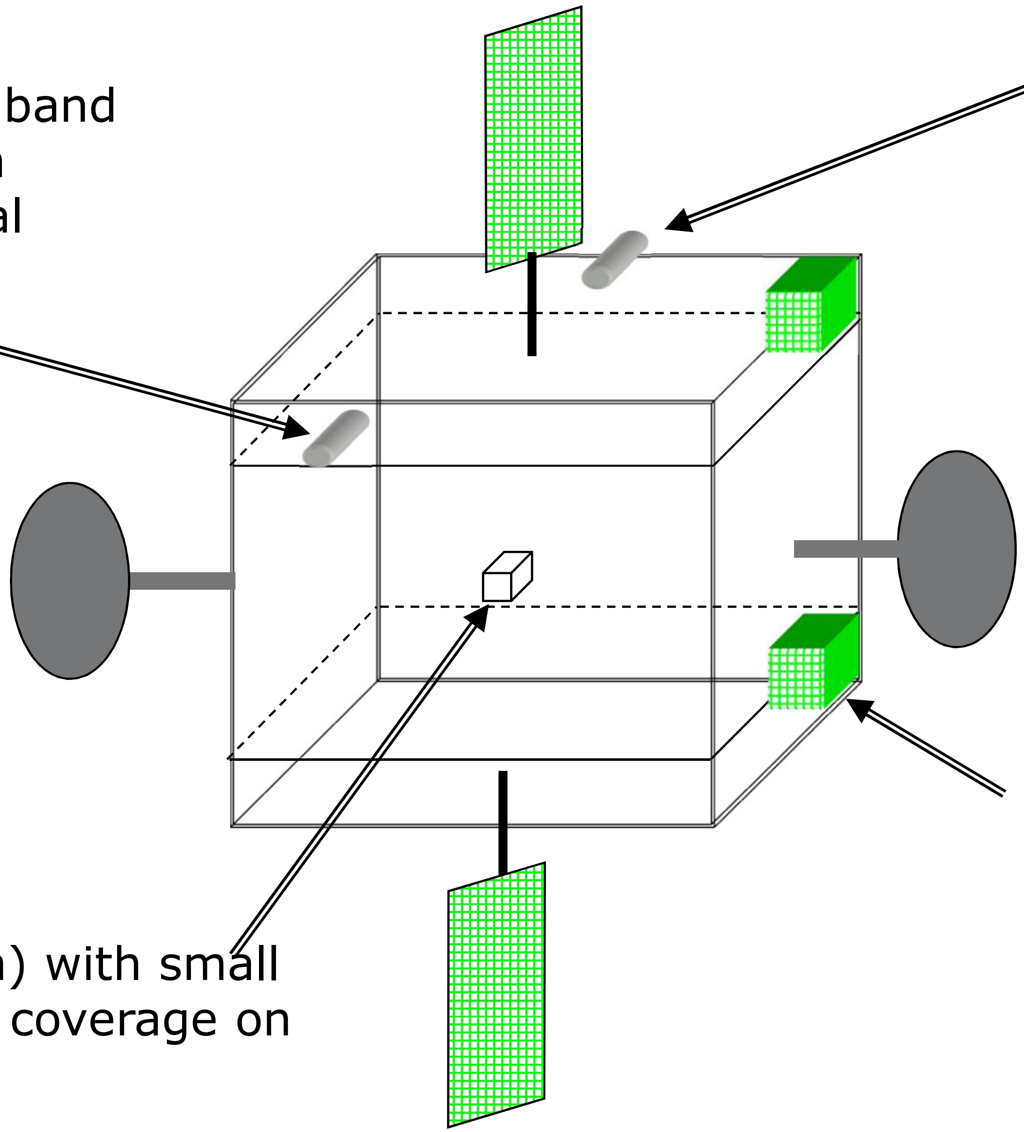
+4 days: Goldstone (35m, higher uplink power) used to send command to switch antennas.

Structural Positions Example

Earth face S band antenna with hemispherical coverage

Anti-earth S band antenna with hemispherical coverage.

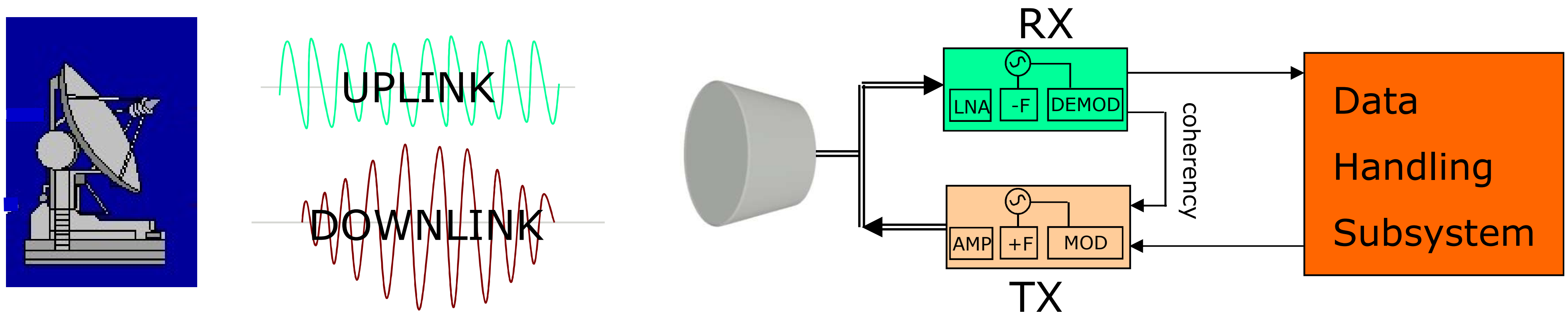
Note: The two S band antennas have opposite polarizations to avoid interference



RX and TX kept on north and south faces with payload equipment to keep them cool

MGA (Horn) with small directional coverage on earth face

REF SUBSYSTEM



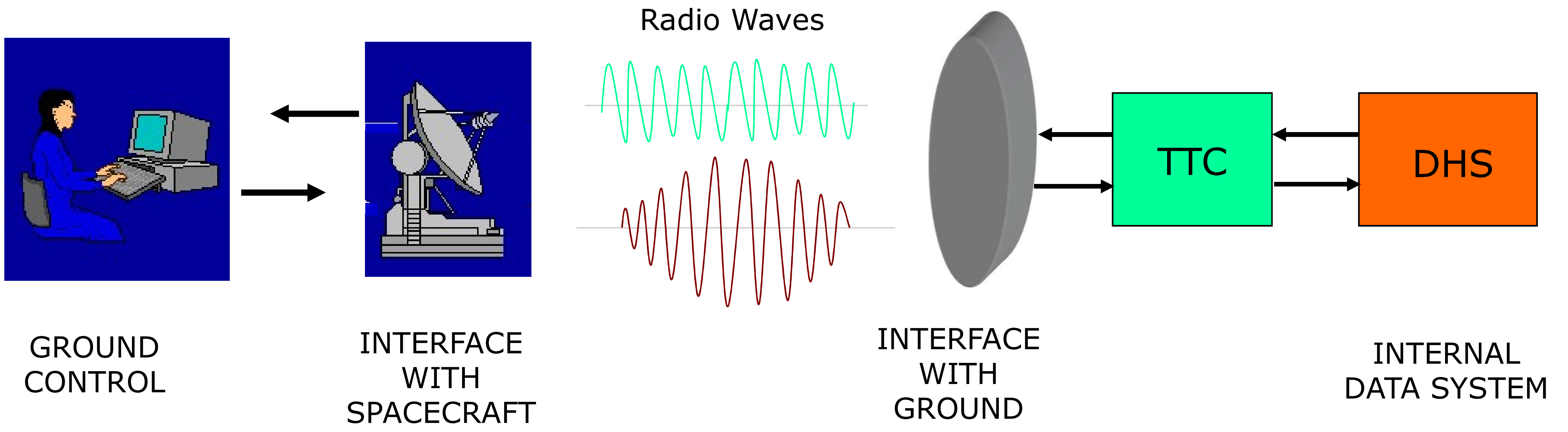
The challenge

The next few slides are to show you that space communications should be impossible

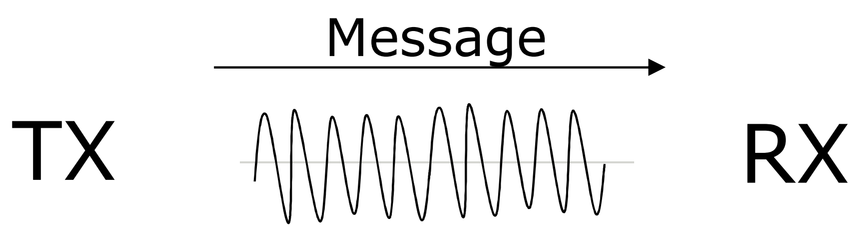
It’s kind of fun to do the impossible

- Walt Disney

Basics

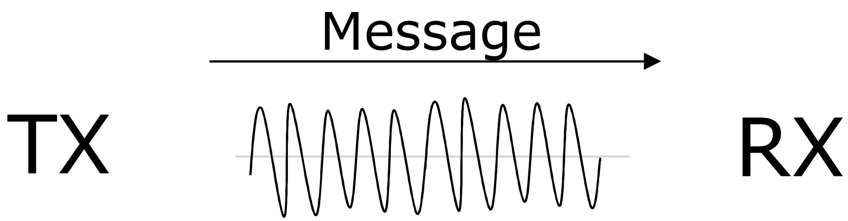


Radio Waves
TTC
DHS
GROUND CONTROL
INTERFACE WITH SPACECRAFT
INTERFACE WITH GROUND
INTERNAL DATA SYSTEM



Message
TX
RX

The challenges…



Between TX and RX

Large and variable distances
Large and variable relative speeds
Variable geometry
Variable medium

Other TXs and RXs

Limited bandwidth
Interference

Spacecraft TXs and RXs

Low power
“Hot”
Limited processing
Limited size

Large and variable distances

MISSION	ALTITUDE (km)
ISS (LEO)	
ENVISAT (LEO)	
GALILEO (MEO)	
MTG (GEO)	
XMM (HEO)	
HERSCHEL (L2)	

Large and variable distances

MISSION	ALTITUDE (km)	2 way Light Time
ISS (LEO)	400	0 s
ENVISAT (LEO)	800	0 s
GALILEO (MEO)	23,000	0.1 s
MTG (GEO)	36,000	0.2 s
XMM (HEO)	2,000 - 120,000	0 - 0.6 s
MOON (ESMO)	380,000	2 s
HERSCHEL (L2)	1,500,000	8 s

Large and variable distances

MISSION	ALTITUDE (AU)
VEX (Venus)	
MEX (Mars)	
Bepi (Mercury)	
ROSETTA (Comet)	

Large and variable distances

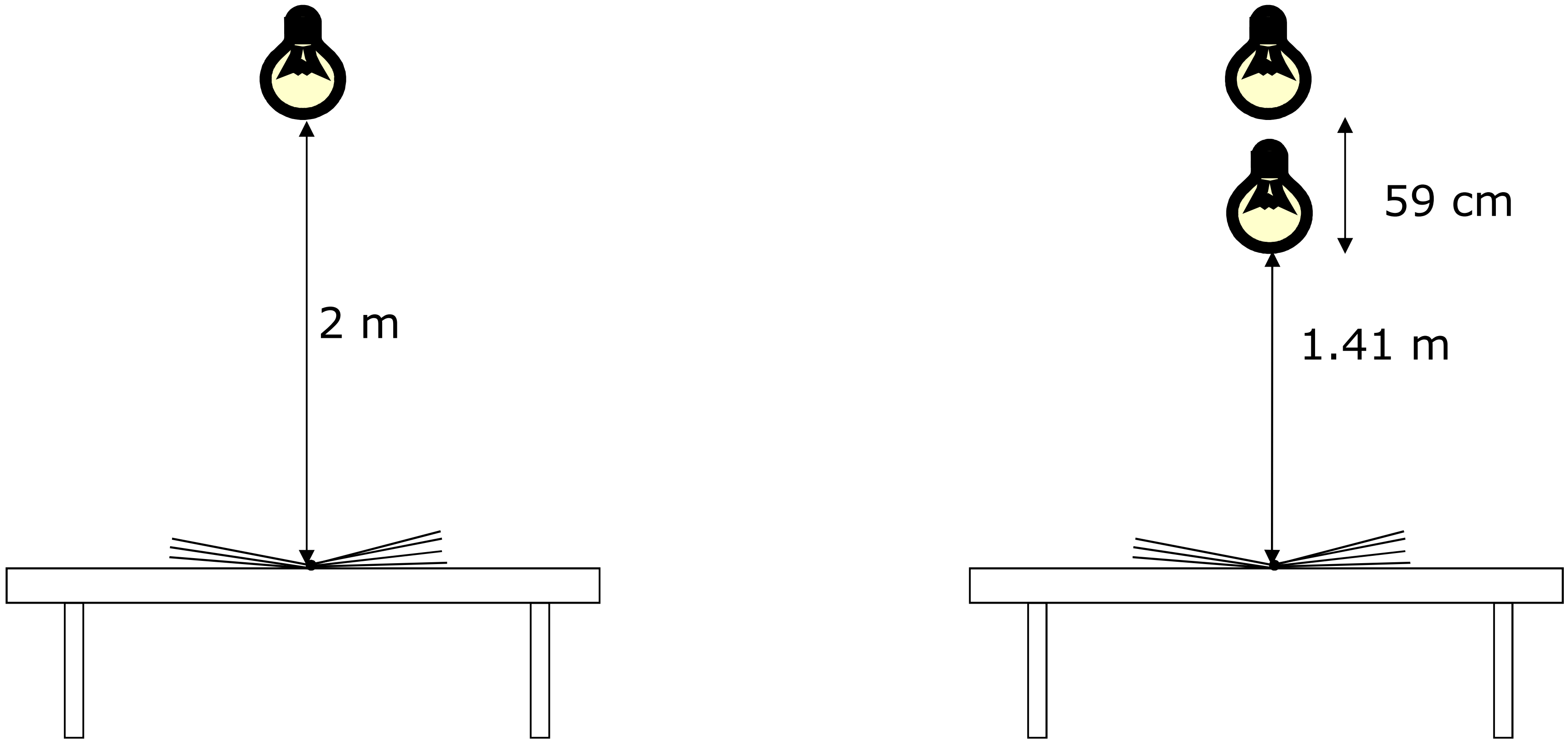
ALTITUDE (AU)	MISSION	2WLT
0.3 - 1.7	VEX (Venus)	4 - 22 m
0.5 - 2.5	MEX (Mars	6 - 33 m
0.7 – 1.3	Bepi (Mercury)	9 - 17 m
0 – 6.2	ROSETTA (Comet)	0 – 81 m

1 AU = 150,000,000 kms
1 light minute = 18 million kms
1 light hour = 1 billion kms
1 light year = 10 trillion kms

Nearest star: 4 light years away

What is the problem?

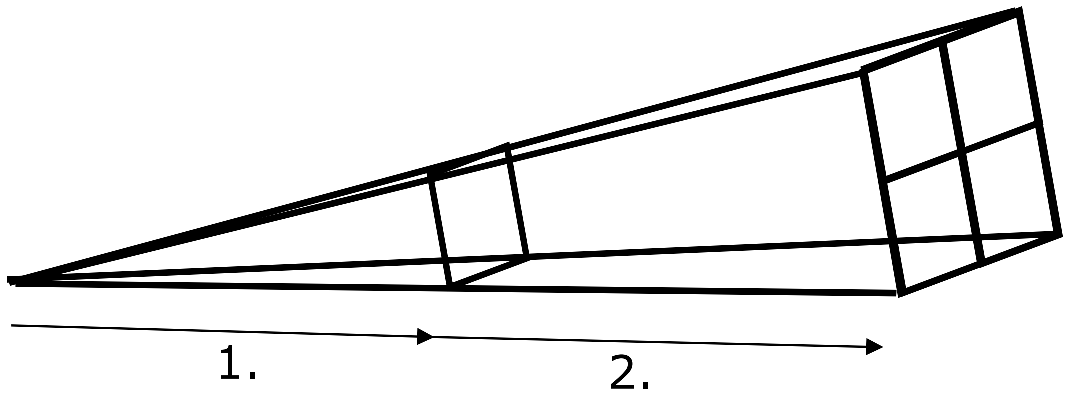
Exercise: If a 100W lamp is 2m above my desk, how far do I have to lower it to make the desk twice as bright?



Now do it in reverse…. moving only 59 cm upwards results in losing half the power

What is the problem?

All electromagnetic radiation starts spreading at a certain distance from the antenna (this is called the 'far field' whereas near the antenna is the 'near field'). Once in the far field it is never a "beam" but a rapidly expanding wave.



The signal spreads according to the square of the distance. Therefore as the diagram shows ; if we double the distance at which we communicate we have to deal with a wave that is 4 times weaker than before.

Quiz

Quiz:

What is the relative power difference between a signal transmitted from the ISS orbit or Mars orbit when it reaches Earth?

Surface area of a sphere ISS = $4 * \Pi * 400{,}000^2 = 10^{12}$

Surface area of a sphere MEX = $4 * \Pi * (2.5 * 150 \times 10^9)^2 = 10^{24}$

Relative power is 10^{12} (a million, million times less)

How much power will left from a omidirectional 10 Watt ROSETTA signal when it is send from the comet rendezvous point (around Jupiter orbit distance)?

Surface area of a sphere at Jupiter = $4 * \Pi * (6.2 * 150 \times 10^9)^2 = 10^{25}$

So the signal power at the Earth will be a 1 millionth, millionth, millionth, millionth of a Watt.

dB

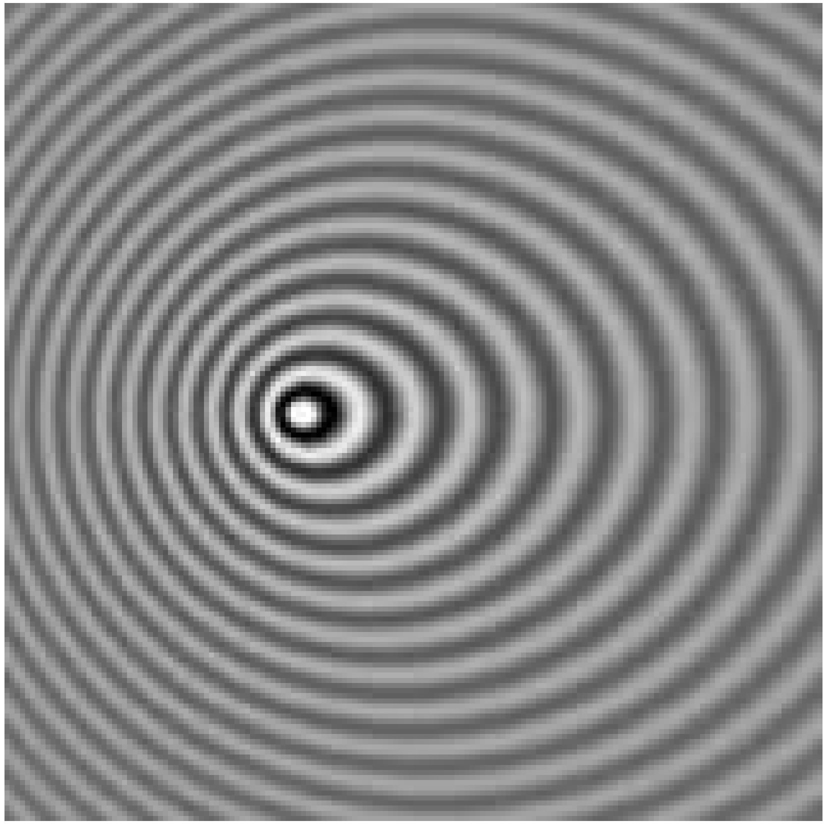
X power	dB
10	**10**
8	**9**
6	**8**
5	**7**
4	**6**
3	**5**
2.5	**4**
2	**3**
1.5	**2**
1.3	1
1	0

20 dB = 100
30 dB = 1000
60 dB = 1 million
etc

dBs are a good way of not having to say a millionth, millionth, millionth… we just say -180 dB

Adding dBs is like multiplying powers which is very useful later..

What’s this?



Large and variable relative speeds

Exercise: ENVISAT makes an orbit every 100 minutes at 800km altitude.
How fast is it going in km/sec? (Earth radius is approx 6400 km)

Answer: **About 7.5 km/s**

2*Π*(6400+800)/(100*60)

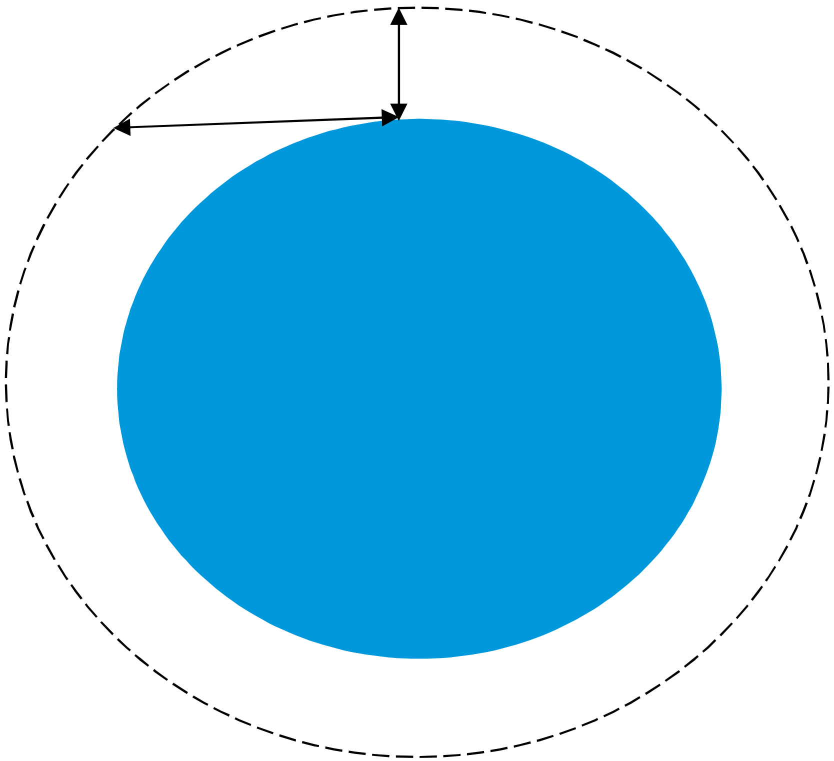
Frequency shift = f * relative velocity of spacecraft/velocity of light

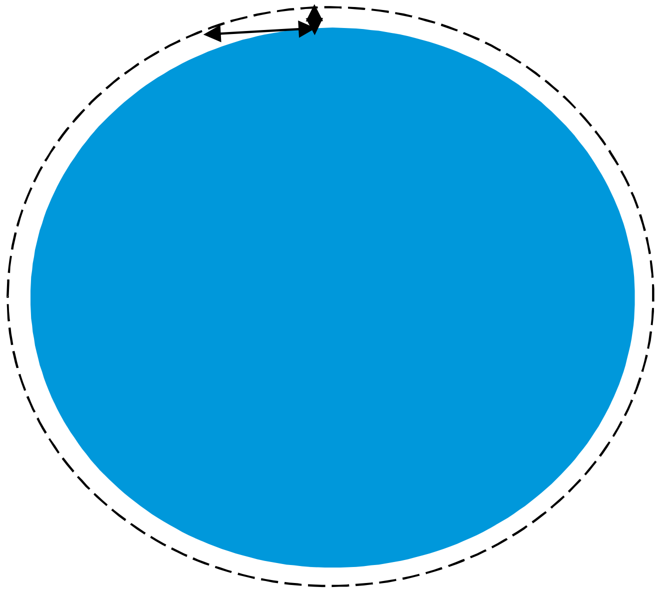
At S band (e.g. 2250 MHz) that gives a shift of 56 kHz
At X band (e.g. 8450 MHz) that gives a shift of 211 kHz

What is the problem?
That is a lot of shift and it is changing rapidly

Fastest spacecraft
Relative to Earth: 265,000 km/h (Juno on Jupiter approach)
Relative to Sun: 253,000 km/h (Helios I)
At Launch: 58,000 km/h (New Horizons)
Look at these in kms per day!

Variable geometry – slant range





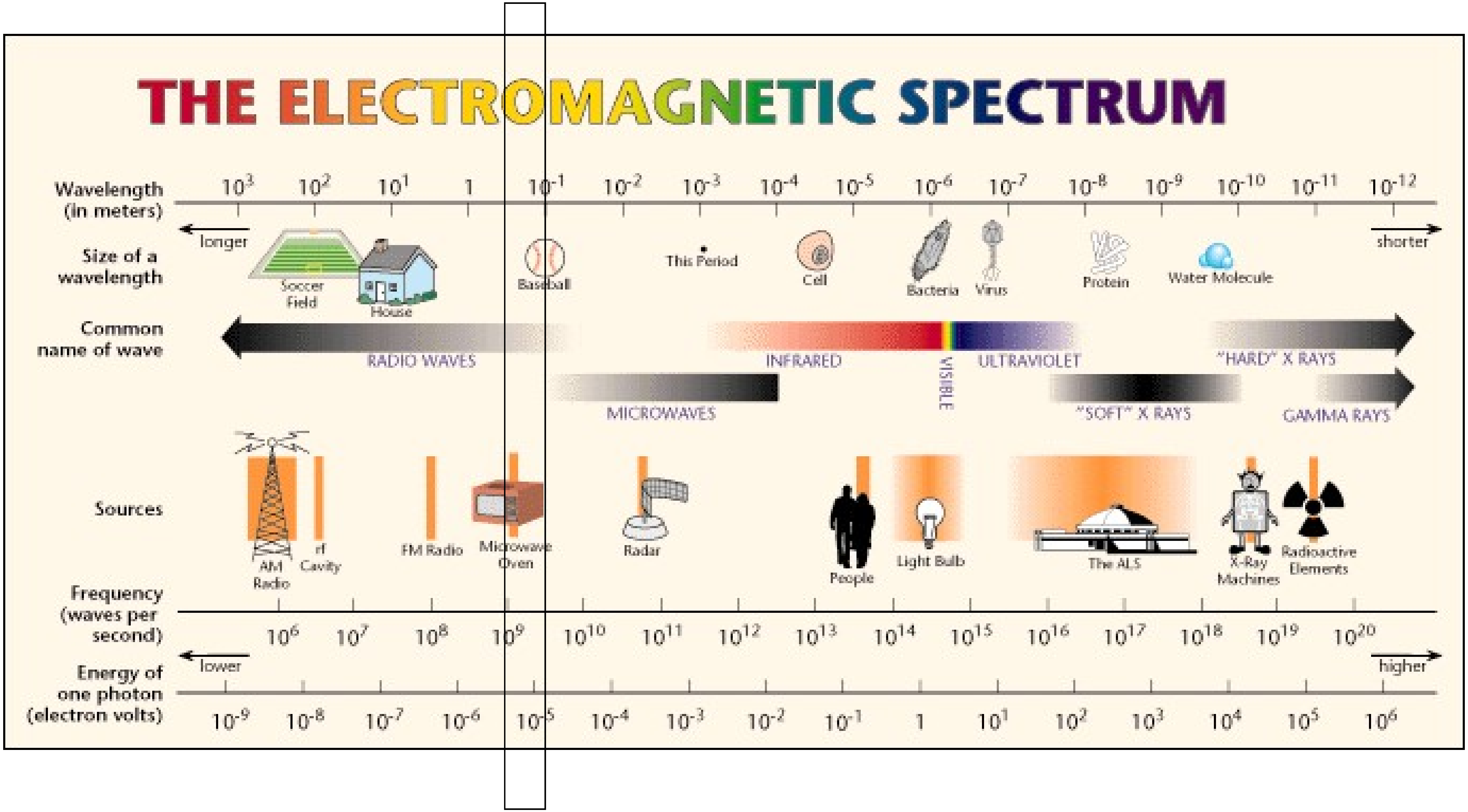
Elevation	Range	%
5°	2784	350%
10°	2367	300%
30°	1395	175%

for a 800km orbit

Elevation	Range	%
5°	1500	500%
10°	1160	390%
30°	564	185%

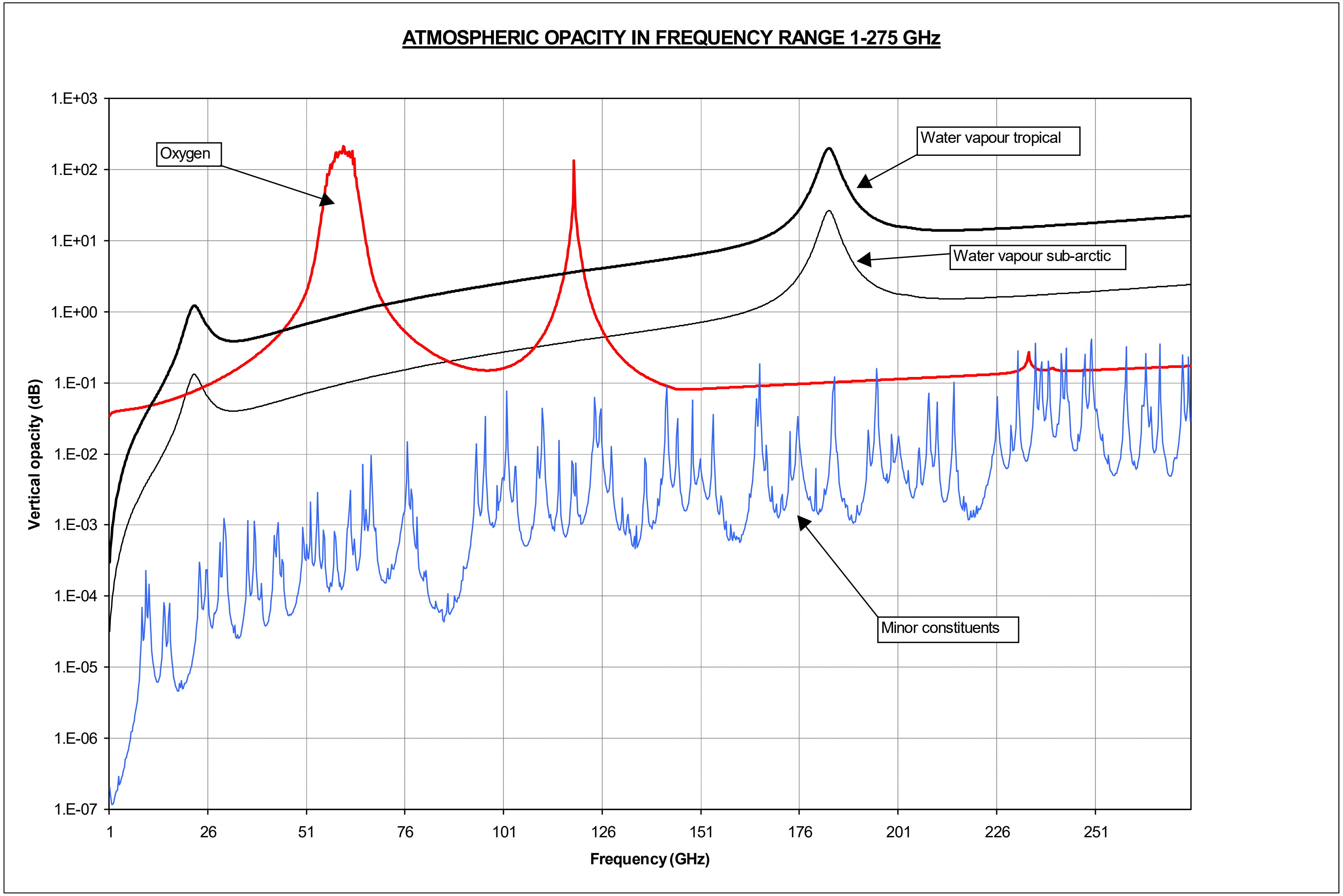
for a 300km orbit

Variable medium



Courtesy of Enrico Vassalo ESA/ESOC

Not so easy to pass through the atmosphere



Courtesy of Enrico Vassalo ESA/ESOC

Therefore frequencies available for space use are limited

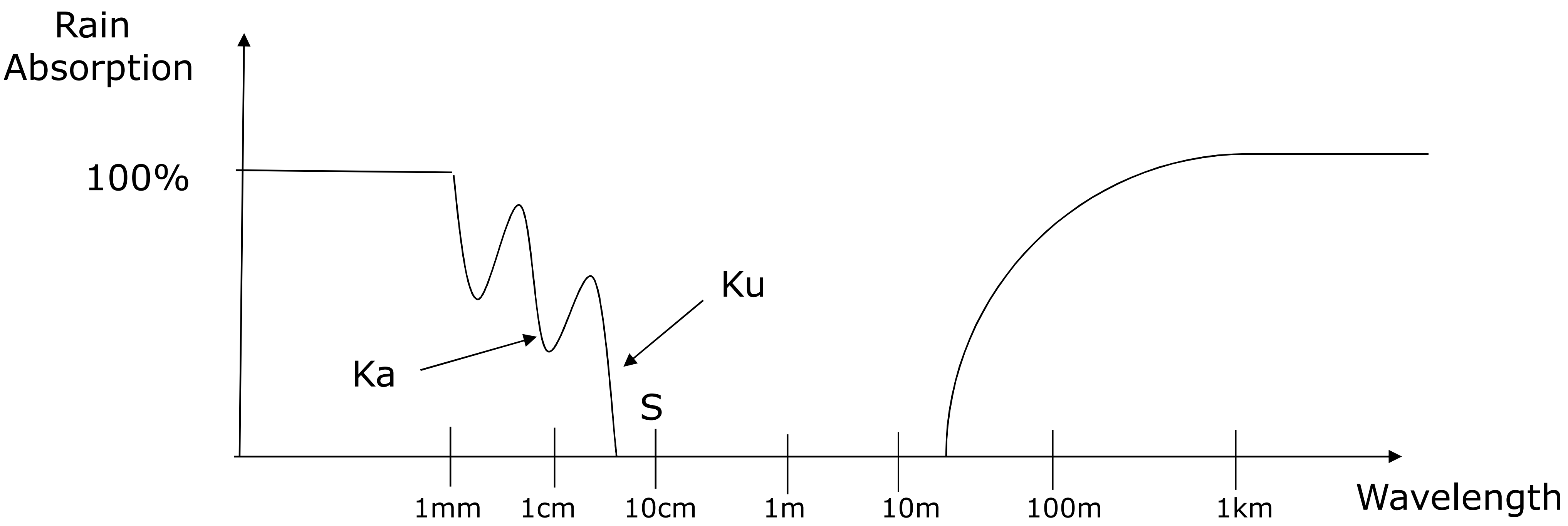
very	VHF	3 – 30 MHz	m
ultra	UHF	0,3 - 3 GHz	tens of cm
super	SHF	3 – 30 GHz	cm

Bands	Frequency
L	1-2 GHz
S	2-4 GHz
C	4-8 GHz
X	8-12 GHZ
Ku	12-18 GHz
K	18-27 GHz
Ka	27-40 GHz

Rain, rain go away....

Atmospheric loss is a big issue for frequencies > 20 GHz (K-Band). It can also be a problem for X-Band in heavy thunder storms and low elevations.

The major absorbing medium is water (water vapor and rain).



Decreasing ground station elevation means the waves must travel through more atmosphere (hence these losses are higher). This effect is relevant for frequencies everything above 5 GHz.

Other variations

- Scintillations caused by electrons in the ionosphere. These cause a lens effect and can increase or decrease the power of the signal,

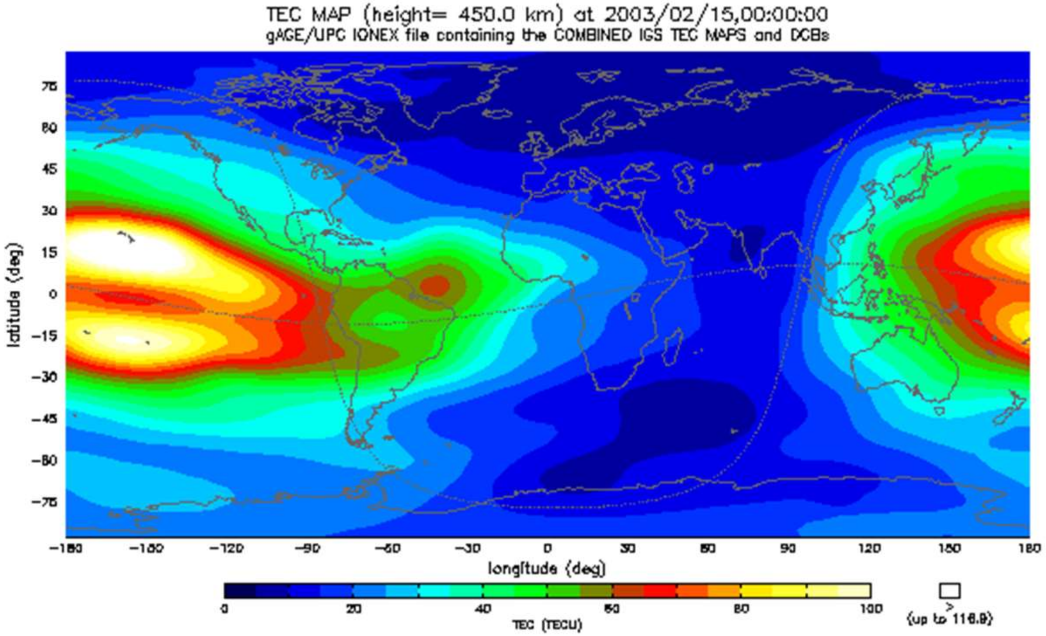
  Low frequencies (UHF, VHF and in special cases S-band) are affected and it can be heavily influenced by space weather.

- Rain can change the polarisation of a wave as it passes through a rain drop. This means that signal strength is lower at the receiver as some of the energy has been transferred to the other polarisation. Most space missions use circular polarisations rather than vertical/horizontal as this effect is much less.

Operational Experience: CLUSTER II and Maspalomas

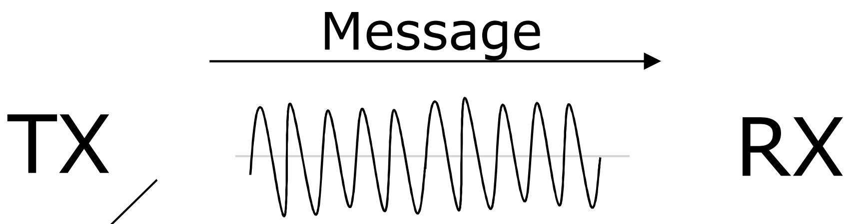
PROBLEM:
2002: CLUSTER II, starts experiencing TM loss problems at Maspalomas.
Station problem suspected

SOLUTION:
Measurement of AGC level in the on-board RX showed the uplink affected as well
Boris and the radio amateurs
It was an equatorial effect in the ionosphere, that affects the equatorial regions.



Courtesy of Enrico Vassalo ESA/ESOC

The challenges...



Between TX and RX

Large and variable distances
Large and variable relative speeds
Variable geometry
Variable medium

Other TXs and RXs

Limited bandwidth
Interference

Spacecraft TXs and RXs

Low power
"Hot"
Limited processing
Limited size

Spacecraft RX/TX limitations

PROPERTY	SPACECRAFT	GROUND STATIONS
Transmit power	A few watts to tens of watts	Up to 20,000 watts (NASA up to 40 KW)
Antenna diameter	A few cm to 3 metres	Up to 70 m
Processing Power	50-200 MIPS	Practically unlimited
Receiver Temperature	290K	With cryogenic cooling down to tens of K

Spacecraft RX/TX limitations

Spacecraft antenna sizes are limited by mass restrictions and volume considerations (especially during launch).

Must fit the antenna folded up inside the narrow fairing for launch

Note the recent interest in deployable and inflatable antennas

Antenna Types

- Low Gain Antennas
  - Coverage of ½ sphere
  - Gain -3dB to 3 dB
- Isoflux Antennas
  - Coverage of Earth with increase at low elevations
  - Gain X-band about 6 dBi (lower gain in S-band due to size limit)
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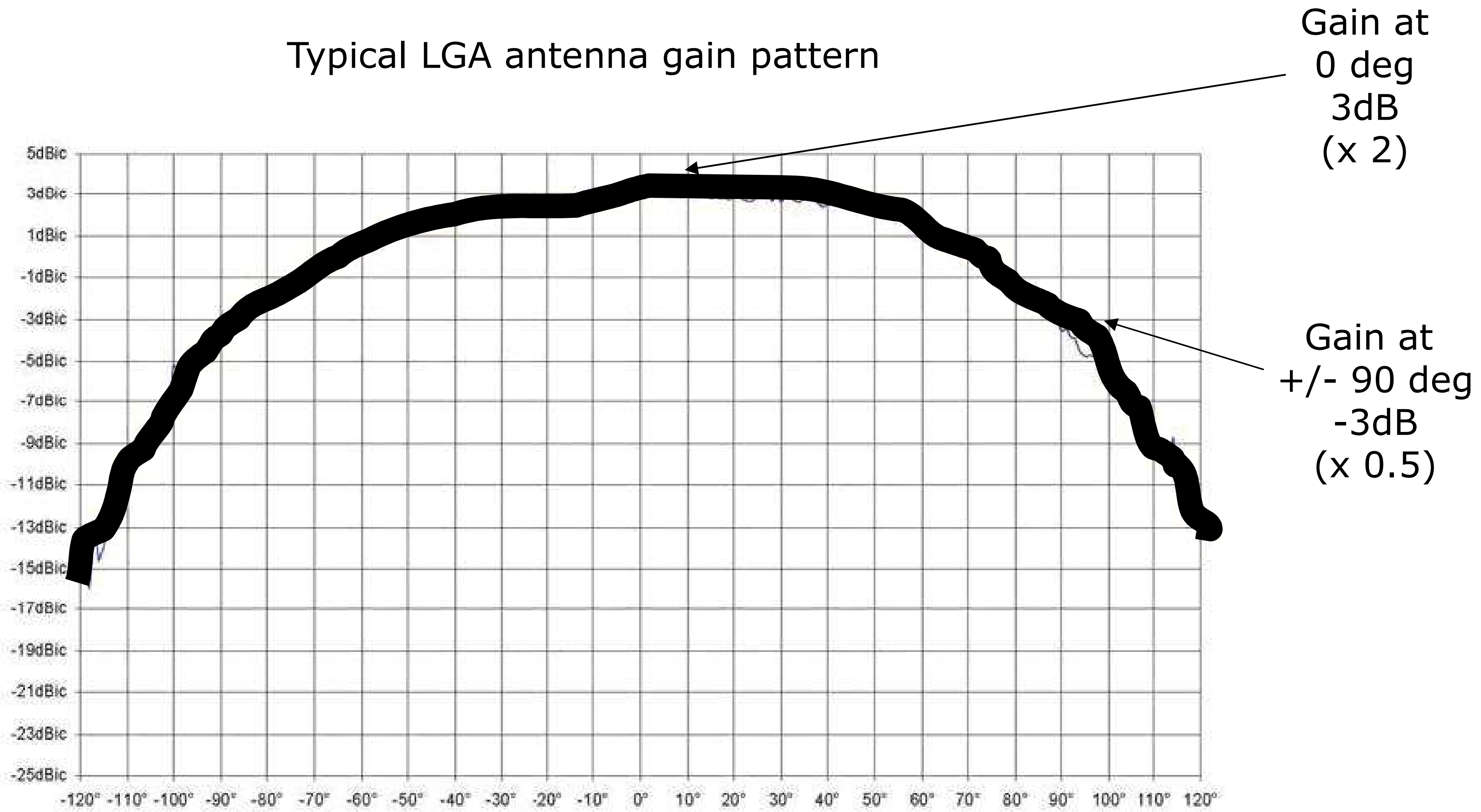
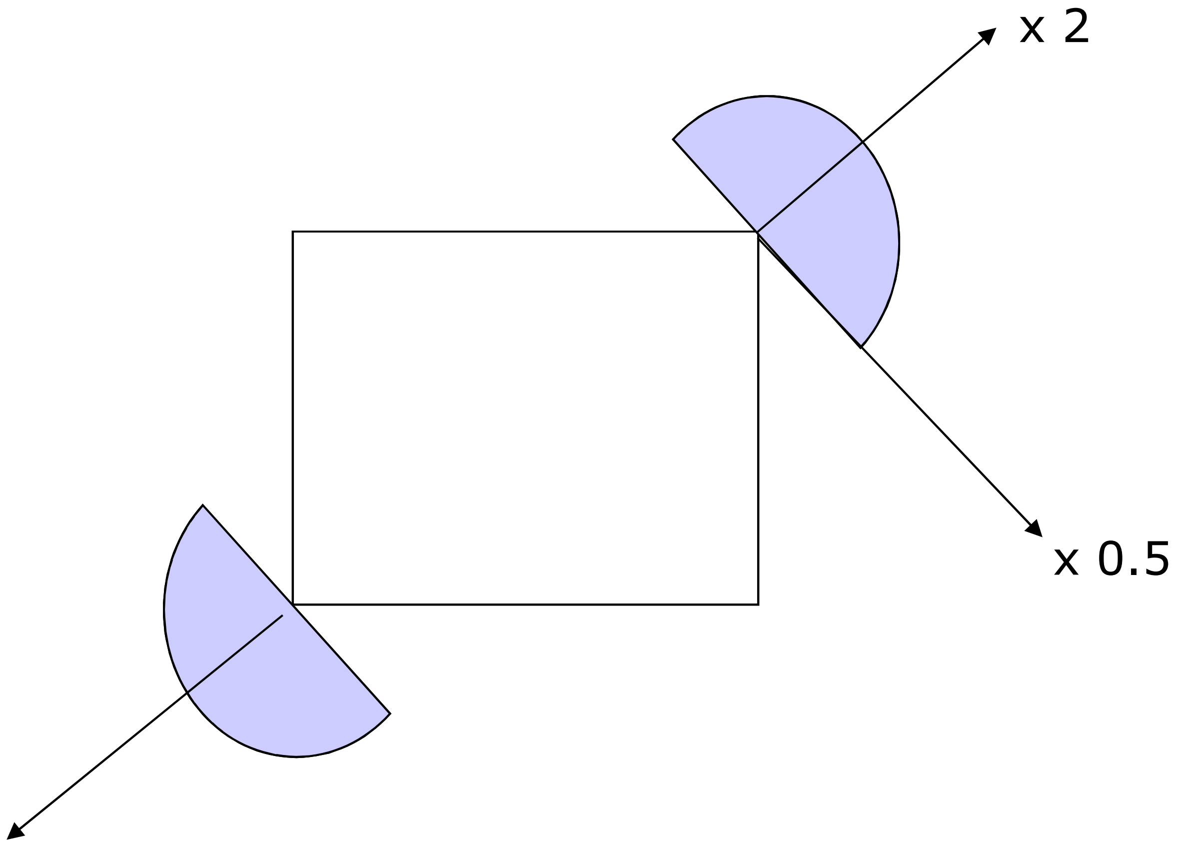
Spacecraft RX/TX limitations

Typical LGA antenna gain pattern



Variable geometry – antenna patterns

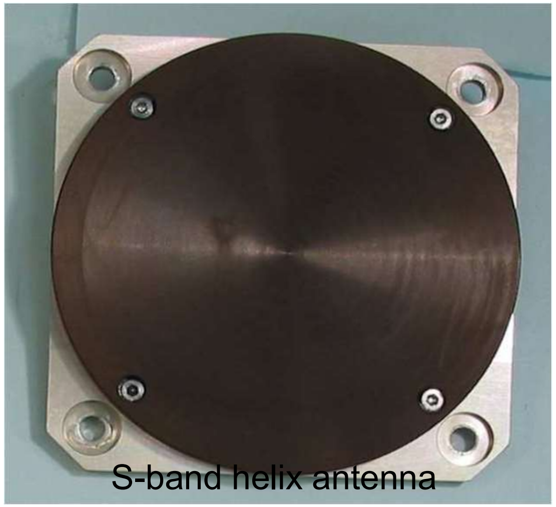
Cannot always point the antennas (e.g. nadir facing earth observation satellite, sun facing, safe mode, launch etc). This introduces even more variation into the strength of the signal received or transmitted.



Low Gain Antenna (LGA)

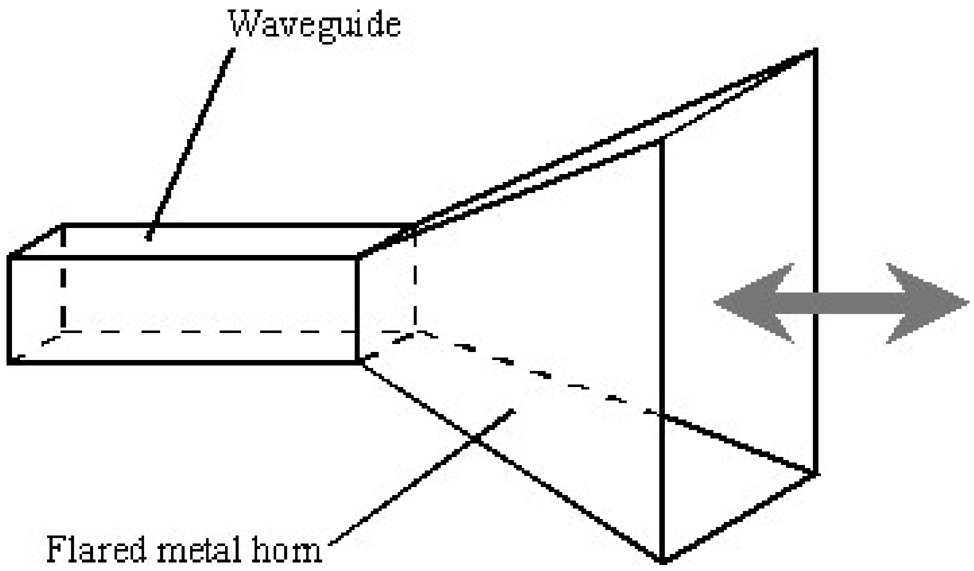
- LGAs are usually mounted at the edges of a spacecraft to provide for unobstructed view into one hemisphere.
- 2 LGAs on opposite sides provide for full sphere coverage. (But if 2 LGA are coupled via a hybrid switch, this means a loss of 3 dB in the signal to noise ratio).
- Actual gain pattern depends very much on interference with satellite body.
- LGAs are used for LEOP and can be used for command and control in general near Earth.
- Use of LGAs is limited for interplanetary missions, even with very large antennas.

X-band helix antenna



S-band helix antenna

Medium Gain Antennas/Antenna horns



Can't get less then 10deg beam width.

15 to 20 dBi typical for S- and X-band.

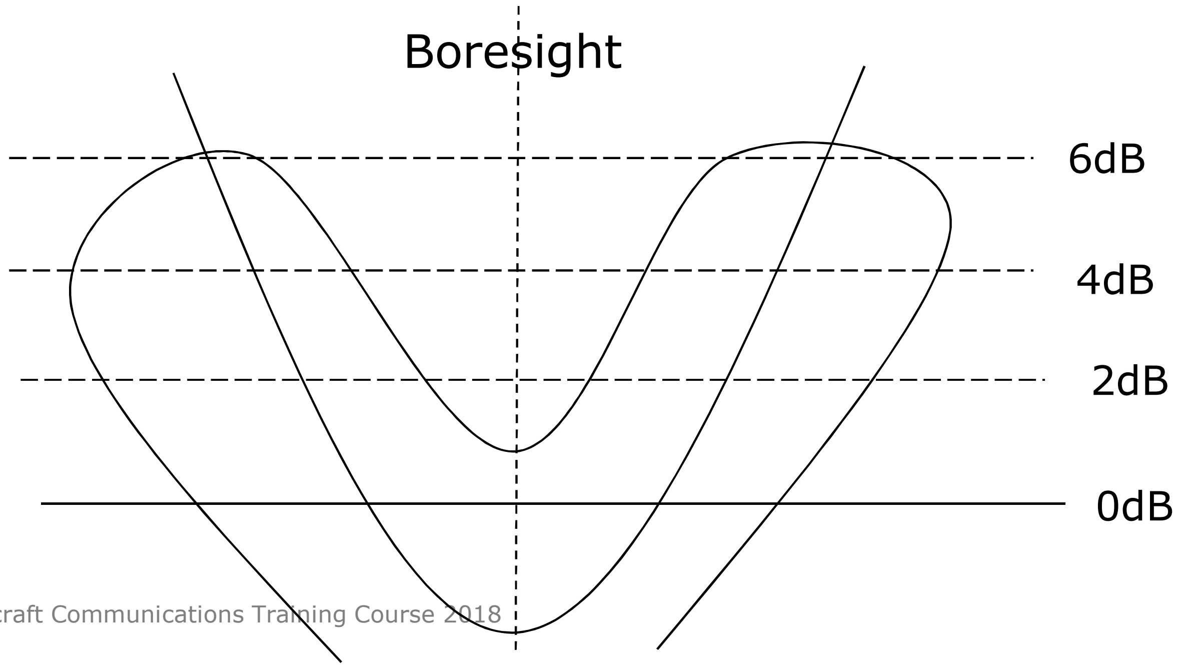
Medium Gain Antennas are HORNS or patched arrays

Isoflux Antenna

Radiate most of their power at 60deg (6dB) at the expense of the centre (0dB).

Makes sense as seen from the ground for a 800km LEO spacecraft the 60deg figure corresponds to a low elevation (5 - 10deg) pass from a ground station on the Earth.

Therefore the power is concentrated where it is most needed (slant range and atmospheric alternation the highest)



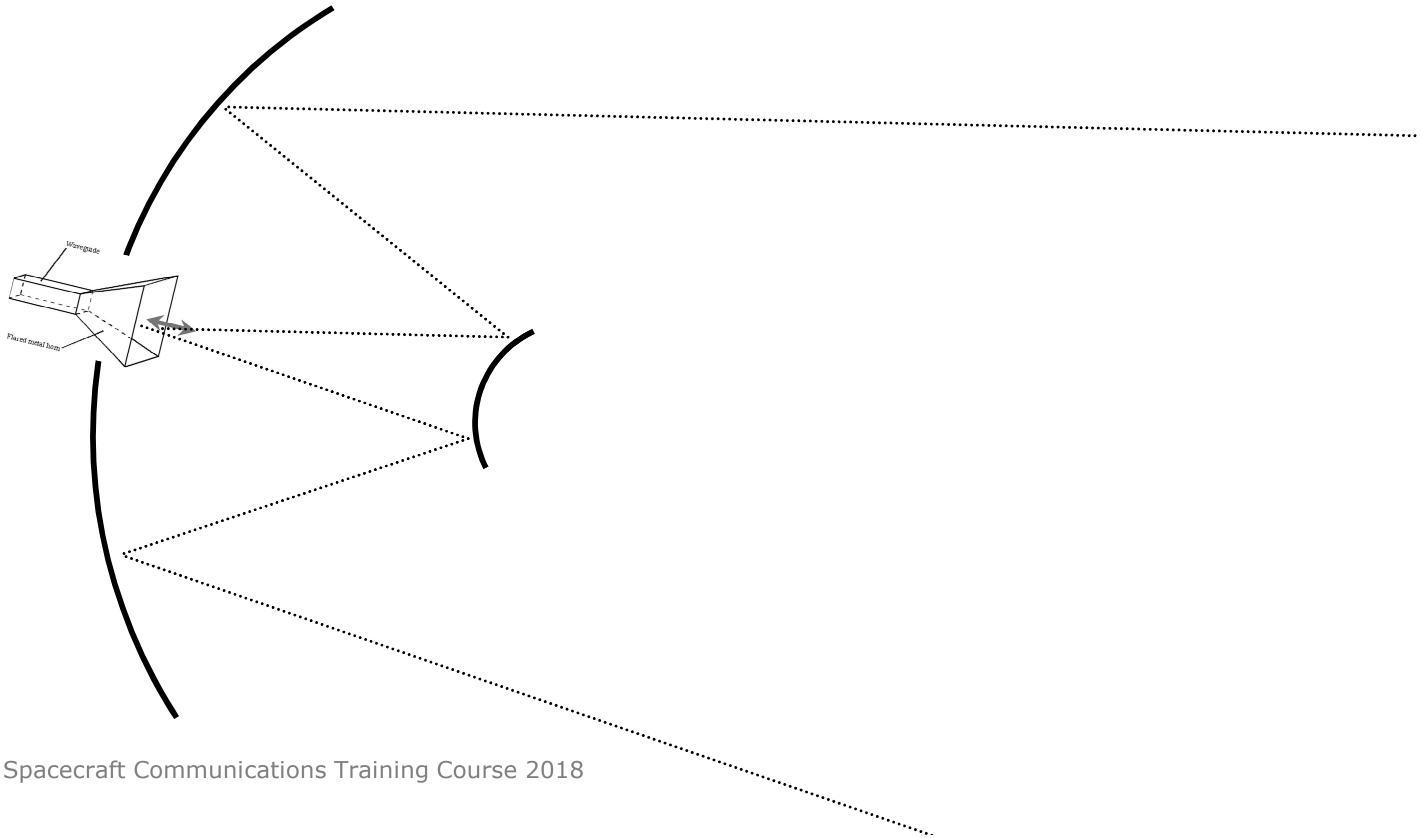
High Gain Antennas/Parabolic Antennas

Very high gain

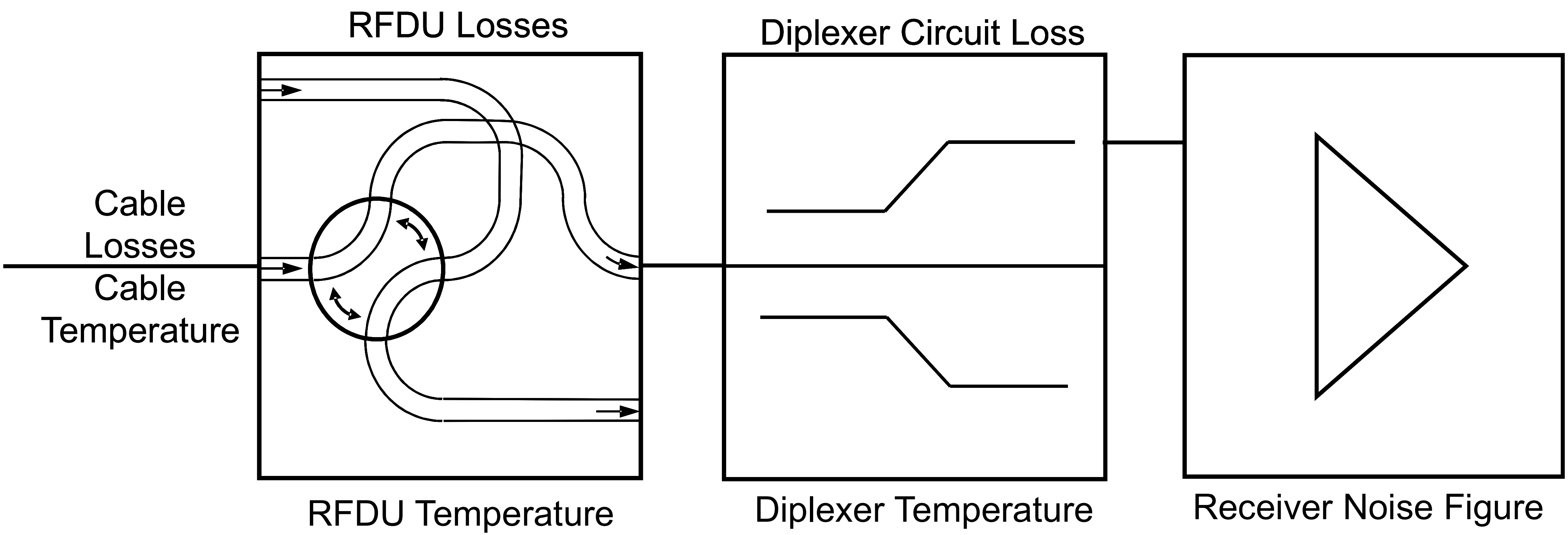
Used for deep space missions

Very large (1m to 3m Ø)

Pointing mechanism required or dedicate attitude for communications

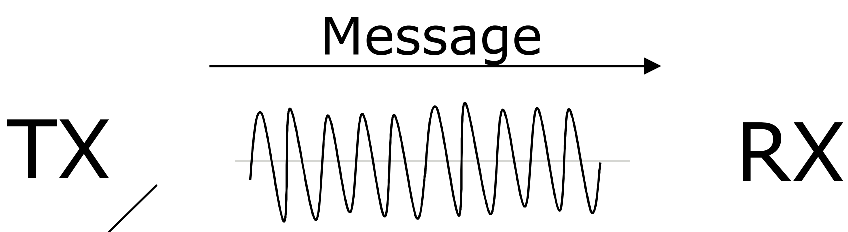


“Hot” Receivers



Courtesy of Enrico Vassalo ESA/ESOC

The challenges...



Between TX and RX

Large and variable distances
Large and variable relative speeds
Variable geometry
Variable medium

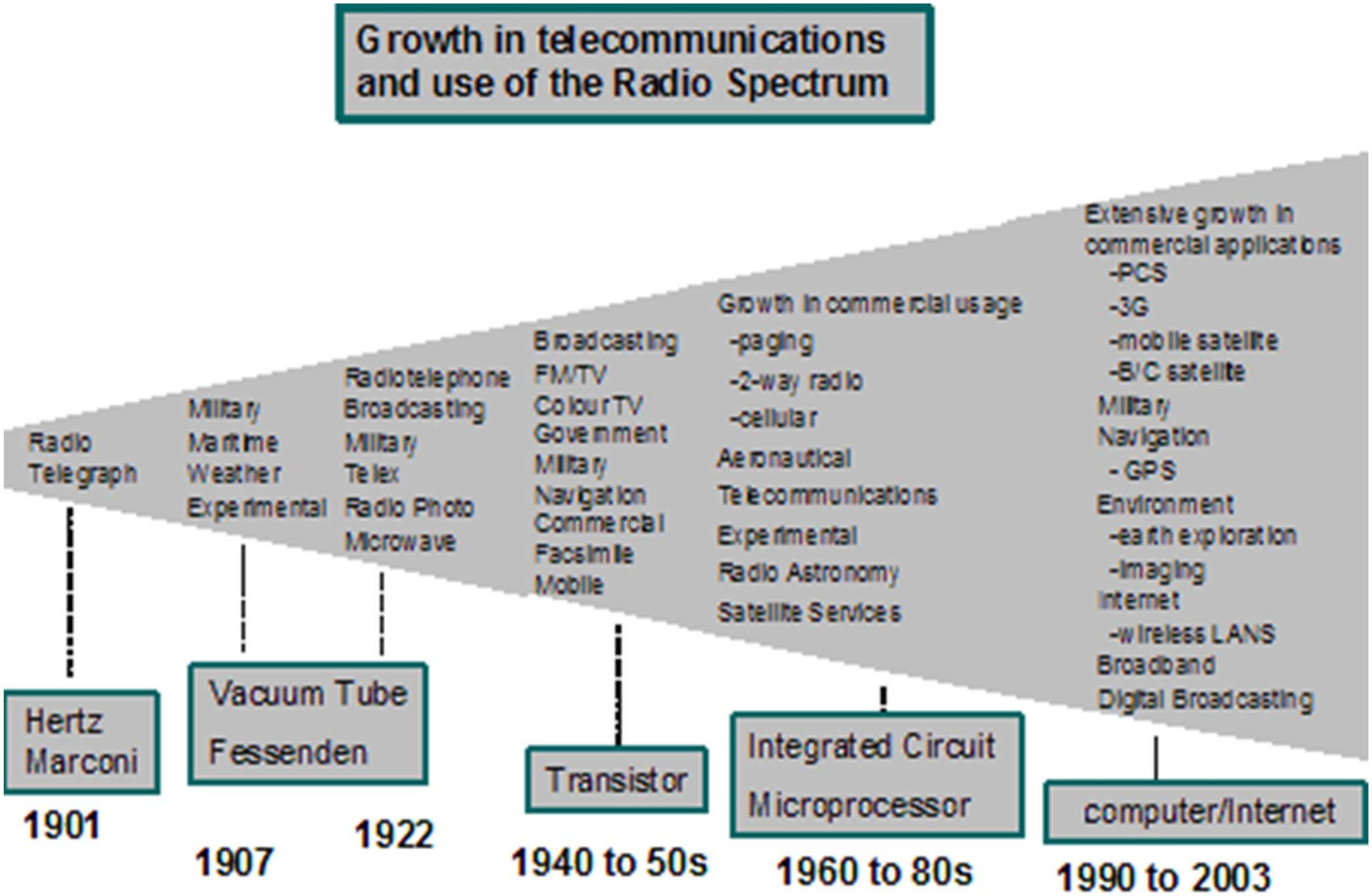
Other TXs and RXs

Limited bandwidth
Interference

Spacecraft TXs and RXs

Low power
“Hot”
Limited onboard processing
Limited size

The spectacular growth of RF users



Courtesy of Enrico Vassalo ESA/ESOC

The value of RF spectrum…

In 2000 the UK government auctioned the frequency licenses for 3G mobile telephones (UMTS). It was only 155 MHz, for 20 years only and only for use in the UK.

QUIZ: How much was the winning bid in euros?

ANSWER: 28 BILLION EUROS

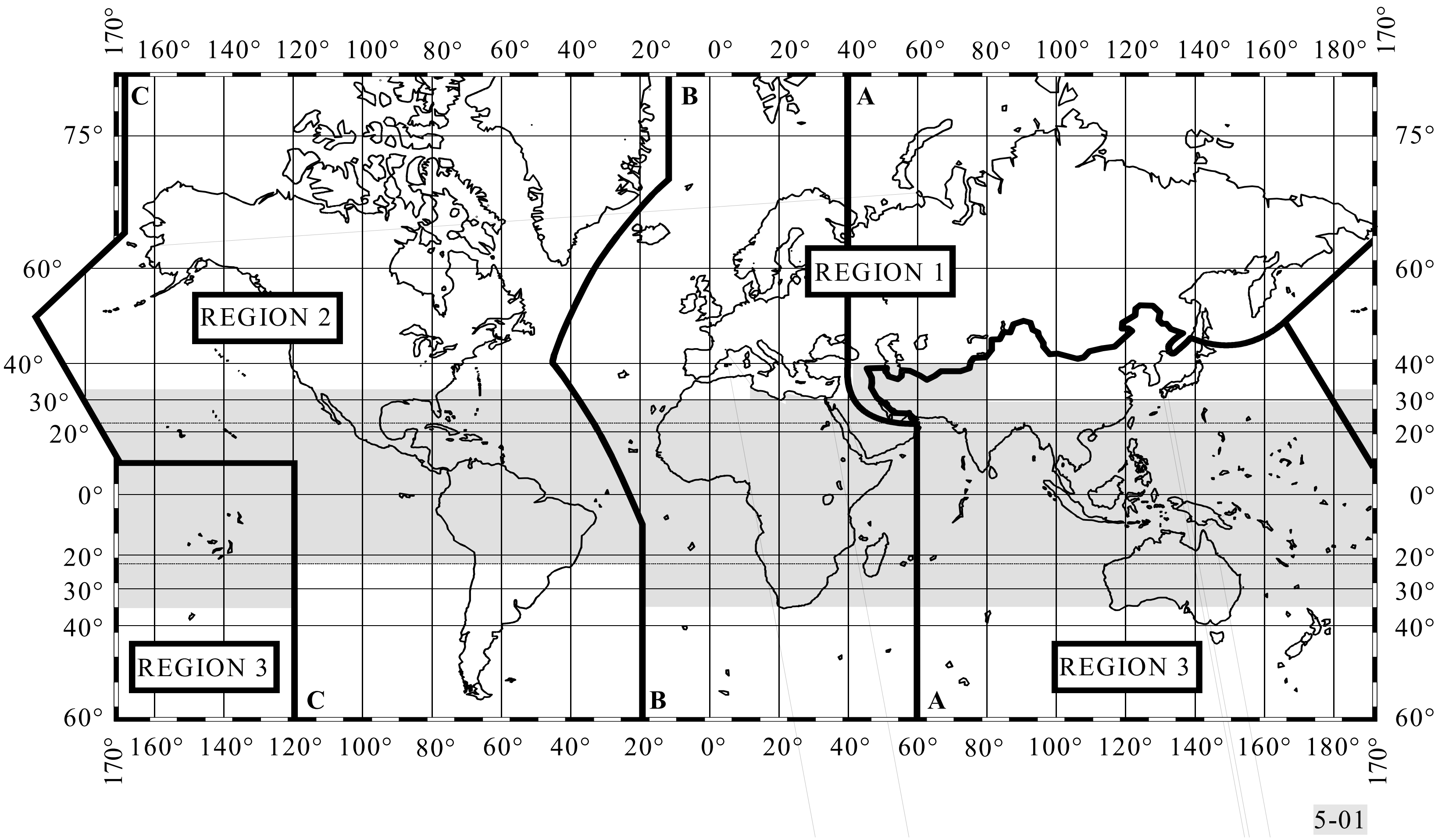
But what's the impact on us?

For the design we are limited in
The **frequencies** we can use
The **maximum bandwidth** we can use in those frequency bands
The **power flux density** of the signal we can radiate on the earth

For the mission we must perform frequency co-ordination for the
Space system
Ground Stations we will use
NB: This is difficult, time consuming process

For ground station design,
Interference with terrestrial systems is very likely if care is not taken on where to place ground stations

The “all powerful” ITU



The spectrum allocation subdivision into 3 Regions

Courtesy of Enrico Vassalo ESA/ESOC

Frequency is allocated by application

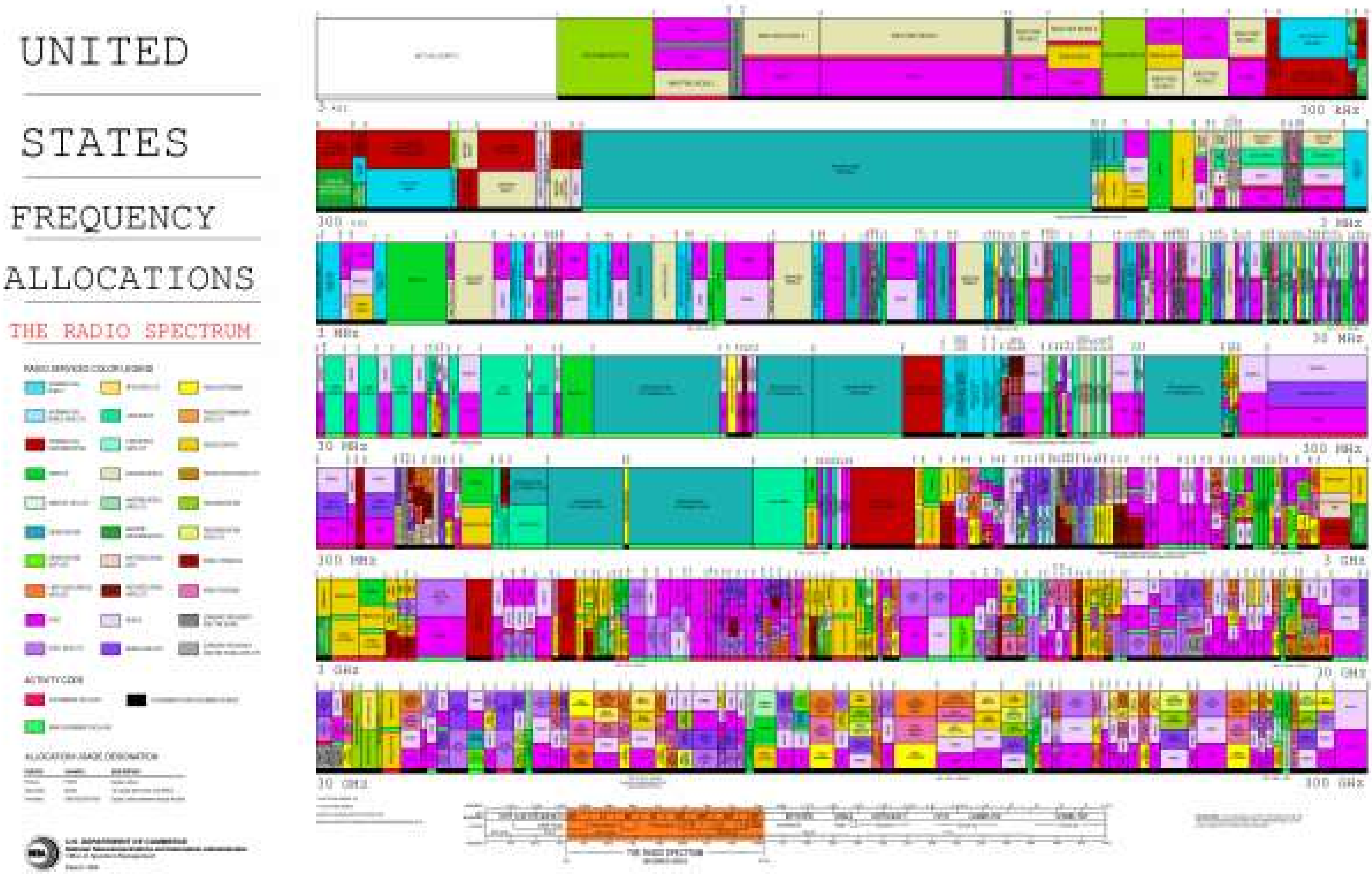
Frequencies are allocated by the ITU according to APPLICATION and you cannot just use whatever you want.

Frequency licensing in the professional world is a very complicated and delicate area.

In our telecom example, the S band that was used for LEOP cannot be used normal operations as the frequency is reserved for low earth orbiters. Therefore another frequency must be used.

The most logical thing for a telecom operator is use part of the payload frequency for command and control and most commercial telecom operators do this.

Frequency Allocation is complicated



Courtesy of Enrico Vassalo ESA/ESOC

An allocation example

Allocation to services		
Region 1	**Region 2**	**Region 3**
1 980-2 010 FIXED MOBILE MOBILE-SATELLITE (Earth-to-space) 5.351A 5.388 5.389A 5.389B 5.389F		
2 010-2 025 FIXED MOBILE 5.388A 5.388B	**2 010-2 025** FIXED MOBILE MOBILE-SATELLITE (Earth-to-space)	**2 010-2 025** FIXED MOBILE 5.388A 5.388B
2 025-2 110 SPACE OPERATION (Earth-to-space) (space-to-space) EARTH EXPLORATION-SATELLITE (Earth-to-space) (space-to-space) FIXED MOBILE 5.391 SPACE RESEARCH (Earth-to-space) (space-to-space) 5.392		
2 110-2 120 FIXED MOBILE 5.388A 5.388B SPACE RESEARCH (deep space) (Earth-to-space) 5.388		
2 120-2 160 FIXED MOBILE 5.388A 5.388B	**2 120-2 160** FIXED MOBILE 5.388A 5.388B Mobile-satellite (space-to-Earth)	**2 120-2 160** FIXED MOBILE 5.388A 5.388B

Basic Communication Frequencies
Space Missions

Band	Application	Uplink [GHz]	Downlink [GHz]	Maximum Downlink Bandwidth
S	Near Earth	2.025 – 2.11	2.20 – 2.29	6 MHz
	Deep Space	2.11 – 2.12	2.29 – 2.3	No restriction < 2 Ms/s
X	Near Earth	7.19 – 7.235	8.45 – 8.5	10 MHz
	Earth Exploration	see above or S-band	8.025 – 8.40	375 MHz
	Deep Space	7.145 – 7.19	8.4 – 8.45	4 – 12 MHz
K	Near Earth	n/a	25.5 – 27.0	1500 MHz
Ka	Deep Space	34.2 – 34.7	31.8 – 32.3	No restriction
Ka	Science	40.0 – 40.5	37.0 – 38.0	No restriction

But remember the other restrictions..

The **frequencies** we can use
The **maximum bandwidth** we can use in those frequency bands
The **power flux density** of the signal we can radiate on the earth

E.g. S band (downlink from space)

Only 90 MHz available for near Earth missions in S band

Max allocation of 6 MHz bandwidth per mission

Bandwidth limitation is defined by a negligible amount of power from your signal outside the allocation NOT useable bandwidth

Power flux density limit of -154 dBW/m^2 (much less than a typical mobile phone power in a cell)

The trend to use higher frequencies

Congestion of frequencies and increasing required bandwidth is generally forcing us to chose higher frequency bands

- **S-Band**
  - Still widely used (but congested)
  - Restricted bandwidth for near Earth missions
  - Conflict for deep space with mobile phone frequencies
- **X-Band**
  - Standard band for new missions, near Earth as well as deep space
  - Higher performance for deep space missions than S-band (for directive antennas)
- **K/Ka-Band**
  - Large bandwidth available for increased data rates
  - Increased navigation accuracy for deep space missions
  - Sensitive to atmospheric attenuation

Practical steps that must be taken early

Satellite systems

Notification of the satellite system can be submitted to ITU from L-3 years. No ‘major’ changes (new frequency band, new on-board antenna, increased power level, etc.) possible after that.

Ground stations

Notification/licensing/authorizations of ground stations to individual countries

No transmission is possible without a notification or a license or an authorization to transmit. Reception is possible without notification/license/authorization but is not protected.

Note:

Transmissions and receptions have to be in line with the obtained licensing data (elevation/azimuth angles, power levels, bandwidth, polarization, support end day, etc.). Monitoring stations are active.

Radio Frequency ESA Standards

- **ESA satellites**

  Radio Frequency and Modulation standard defined in:

  - ECSS-E-ST-50-05C

    (ECSS = European Cooperation For Space Standardisation)

  - ECSS standards are applicable for European industry and agencies (for communications and other fields of engineering)

  - ECSS communication standards are a tailored subset of CCSDS standards

    (CCSDS = Consultative Committee for Space Data Systems)

  - CCSDS and ECSS follow ITU regulations

    (ITU = International Telecommunication Union)

- **Radio Amateur Satellites**

  Communication frequencies and usage defined by ITU regulations

Other users and Ground Station Design

What have the following got in common?

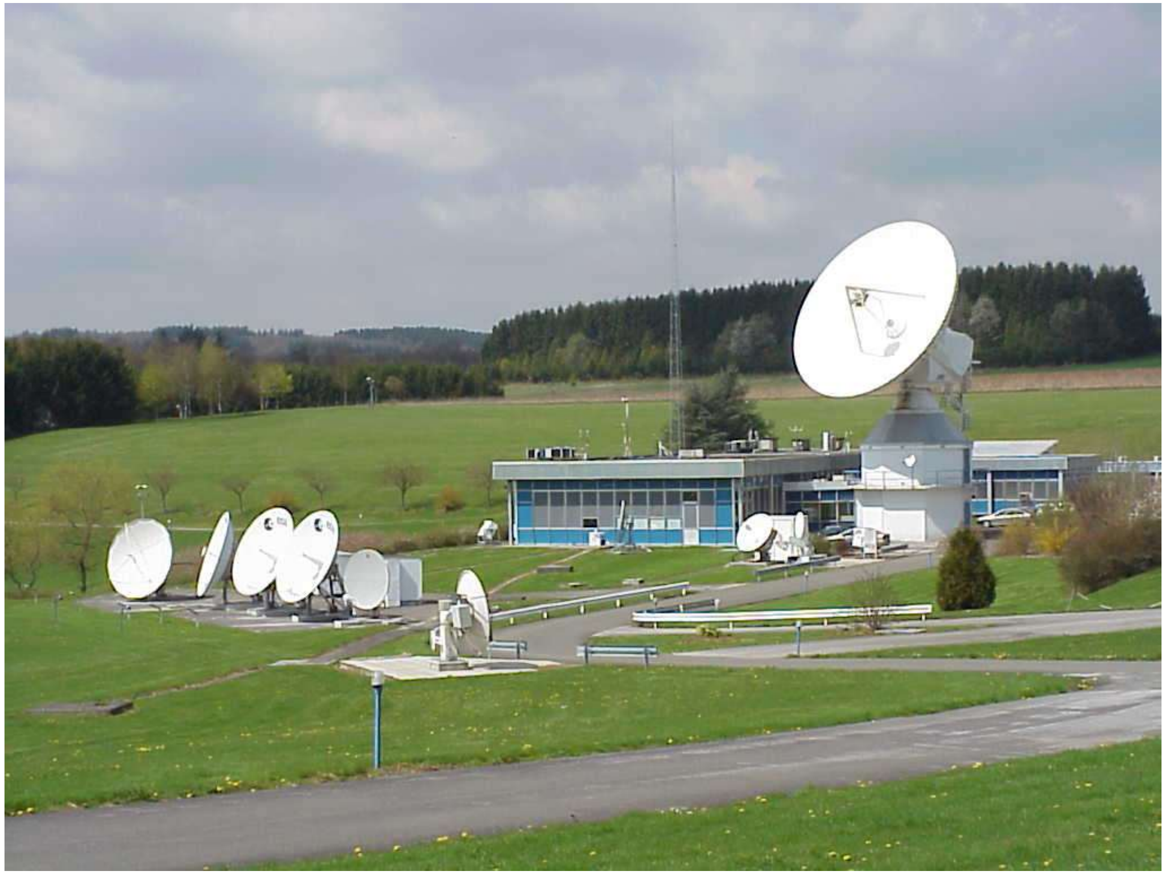
UMTS mobile telephones	and	Interplanetary missions command systems ?
Latest generation Wi-fi	and	Satellite SAR (Envisat, Sentinel-1) ?
Tour de France helicopter cameras	and	Operations from our Redu (B) station ?
Car anti-collision systems	and	Satellite atmospheric sounders (MetOp) ?
Remote location TV-news links	and	Operations from our Perth (AUS) station ?

They all share the same frequencies and could interfere!

Courtesy of Enrico Vassalo ESA/ESOC

Ground Station Design

This is the ESTRACK Redu station. What is strange about the location of the antennas?



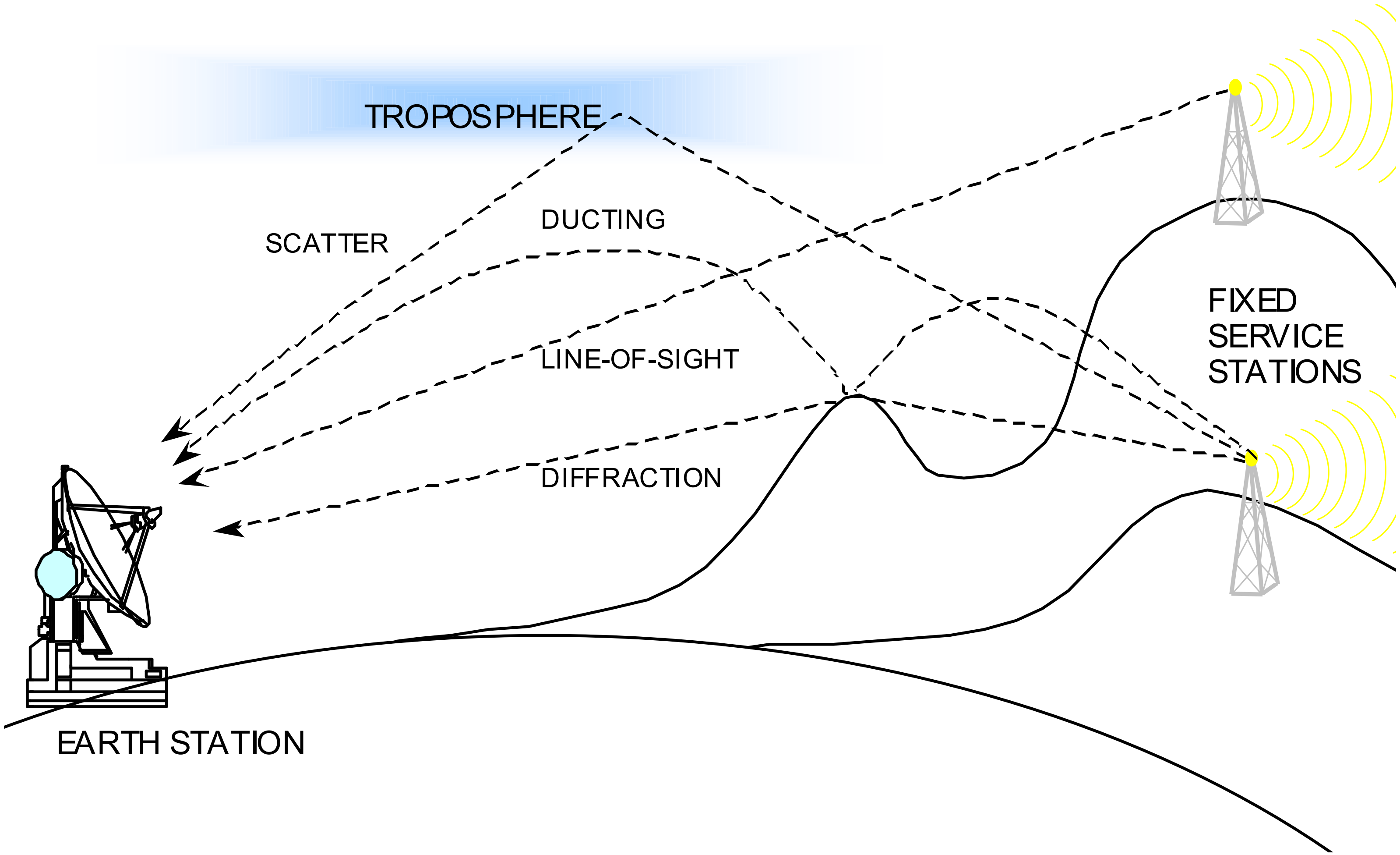
Other users and Ground Station Design

Protection from radio interference is a key element in the selection of where to install a ground station:

Suitable natural shielding,
Limited number of potential RFI sources in the vicinity,
Sizable distance from urban areas

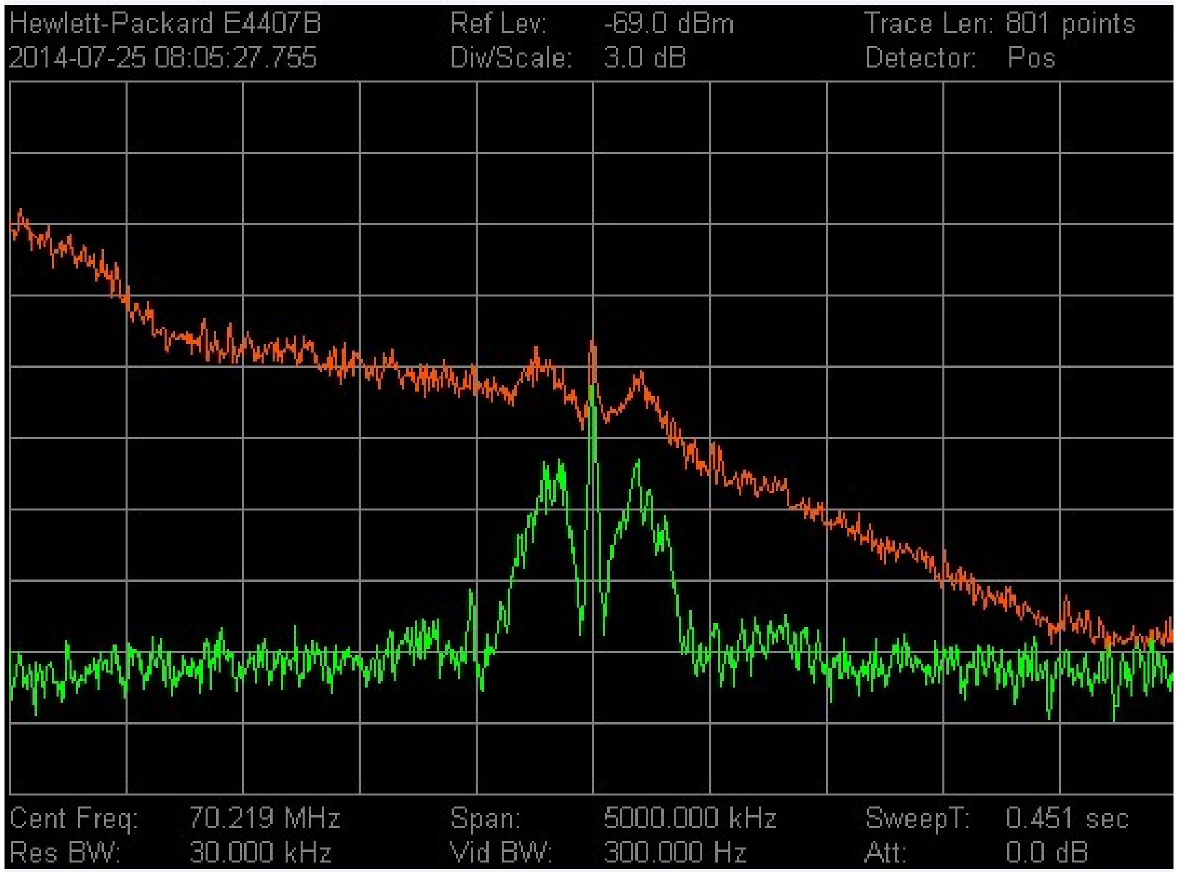
Remember
As well as receiving a weak signal we are also blasting out a very strong one

Ground Station Design



Courtesy of Enrico Vassalo ESA/ESOC

What does interference look like?

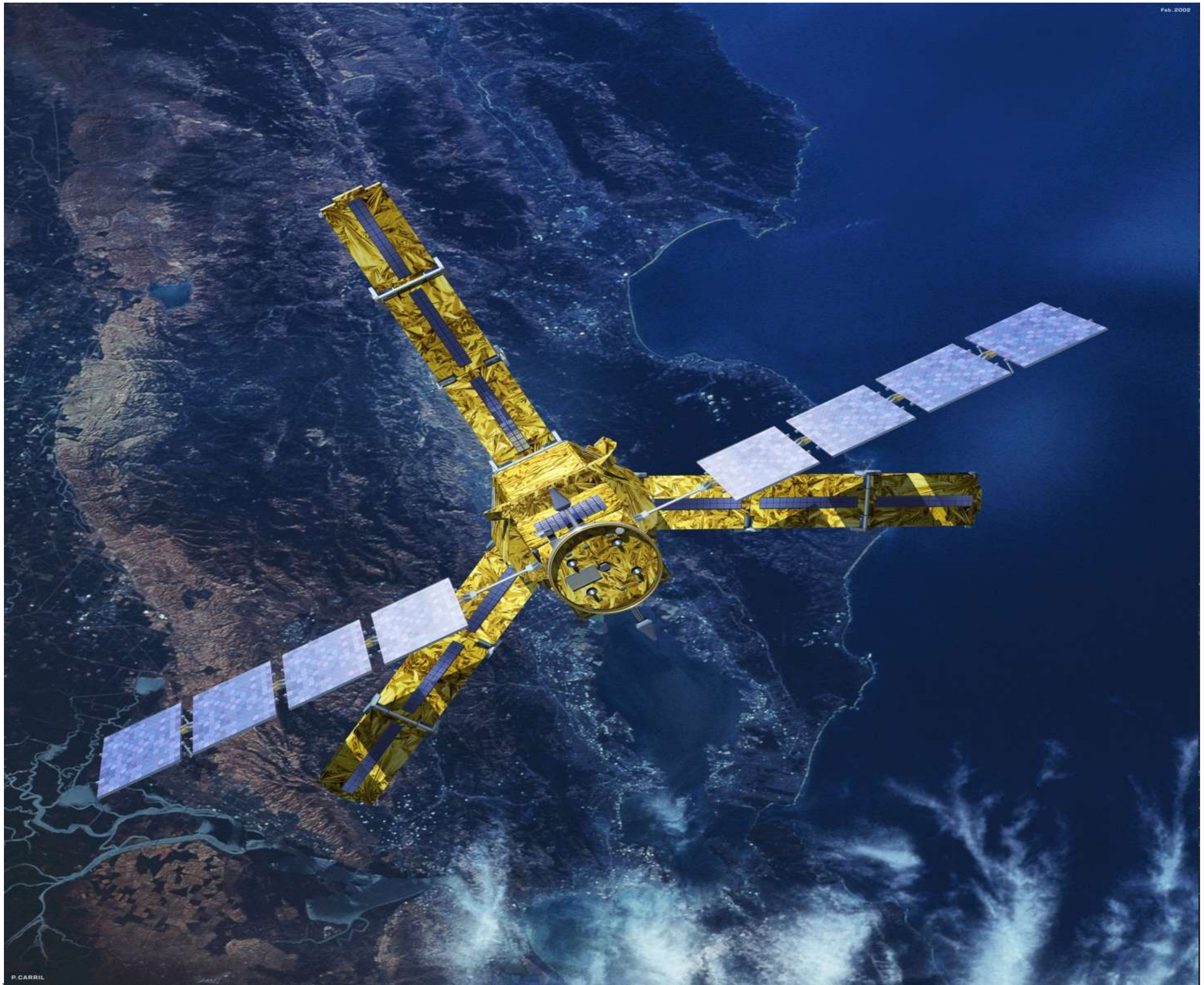


Here is the spectrum capture of Integral and a Russian GLONASS navigation satellite causing RFI.

Integral alone is in the clear/write trace in green and with RFI is shown in the max hold trace in red.

Courtesy of Sam Peterson ESA/ESOC

Real interference example

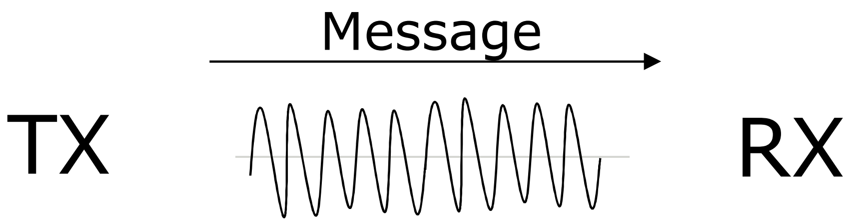


SMOS: Launched 2 November 09 from Plesetsk on Rockot

Innovative L band radar to monitor surface soil moisture. 8 m across – “helicopter”.

Effectively blinded in some areas of the world due to interference.

Summary



Between TX and RX

Large and variable distances
Large and variable relative speeds
Variable geometry
Variable medium

Other TXs and RXs

Limited bandwidth
Interference

Spacecraft TXs and RXs

Low power
“Hot”
Limited processing
Limited size

Basic Communications/Data Rate Constraints (RF)

- **Signal to Noise Ratio**

  Available signal to noise ratio may limit ability of ground station to track the signal or limit data rate. Signal to noise ratio may be limited by:

  - Power of transmitter
  - Antenna size on board and/or on ground
  - System temperature of receiving antenna

- **Bandwidth**

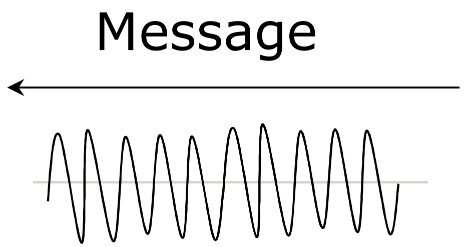
  Limits depend on:

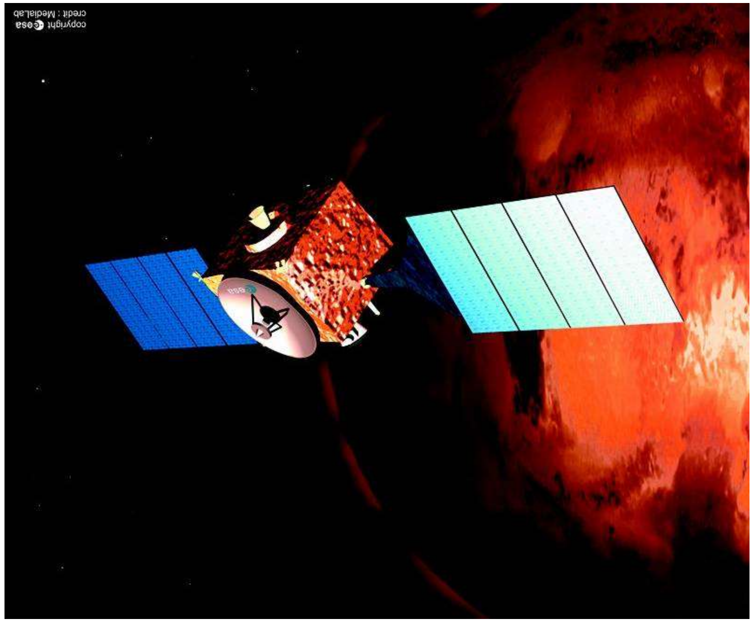
  - Type of mission (near Earth or deep space)
  - Frequency band
  - Technical implementation (e.g. modulation scheme)

- **Flux Density**

  RF flux density may not exceed certain values on Earth surface

Now just imagine the difficult journey of a message from a deep space probe





Your mission now is to design a communications system which is capable of retrieving that message!