The ladybird guides

Book II

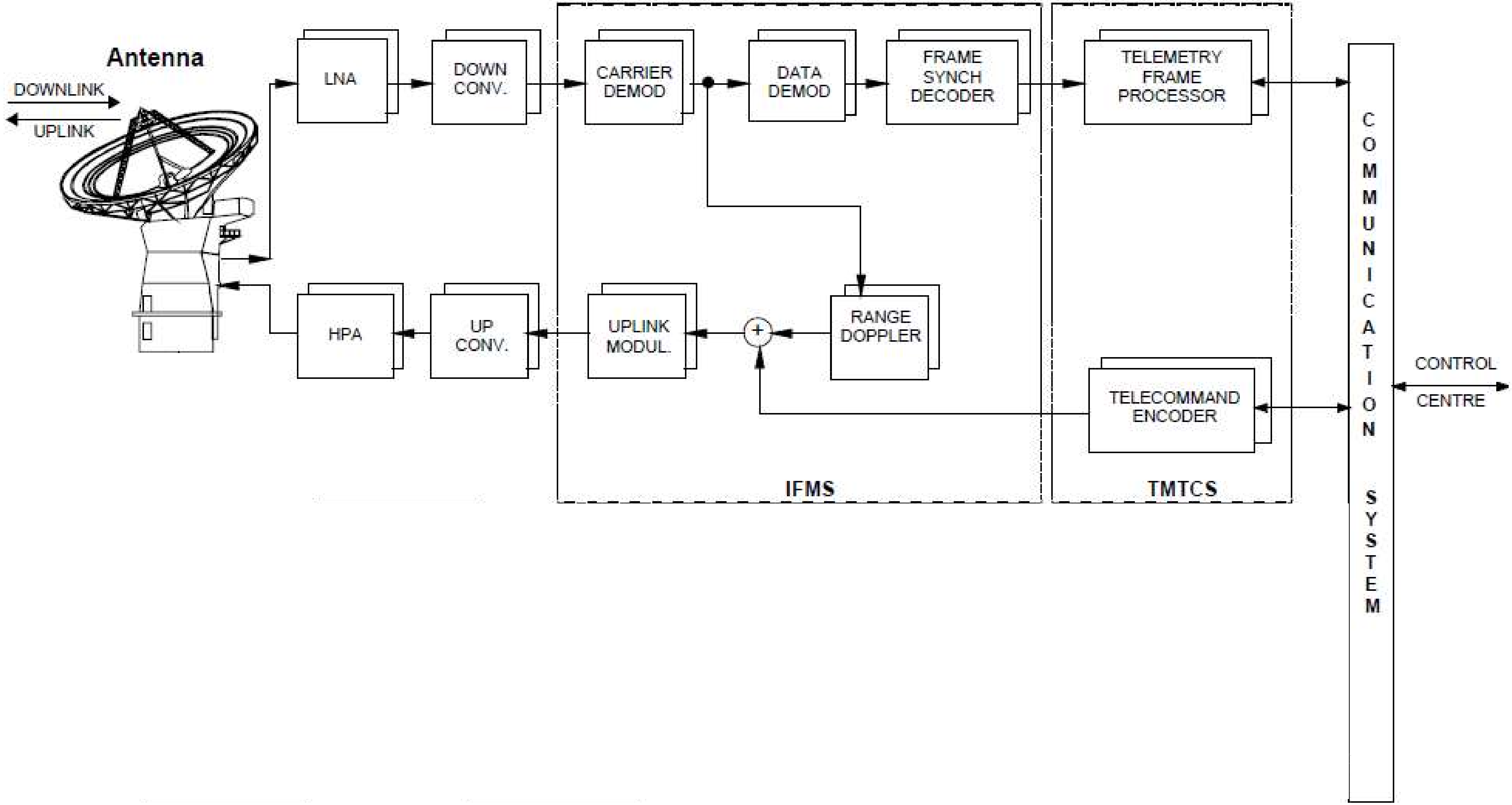
Day 6 – Transmission

Day 6: Link Budgets: Transmission and Travel

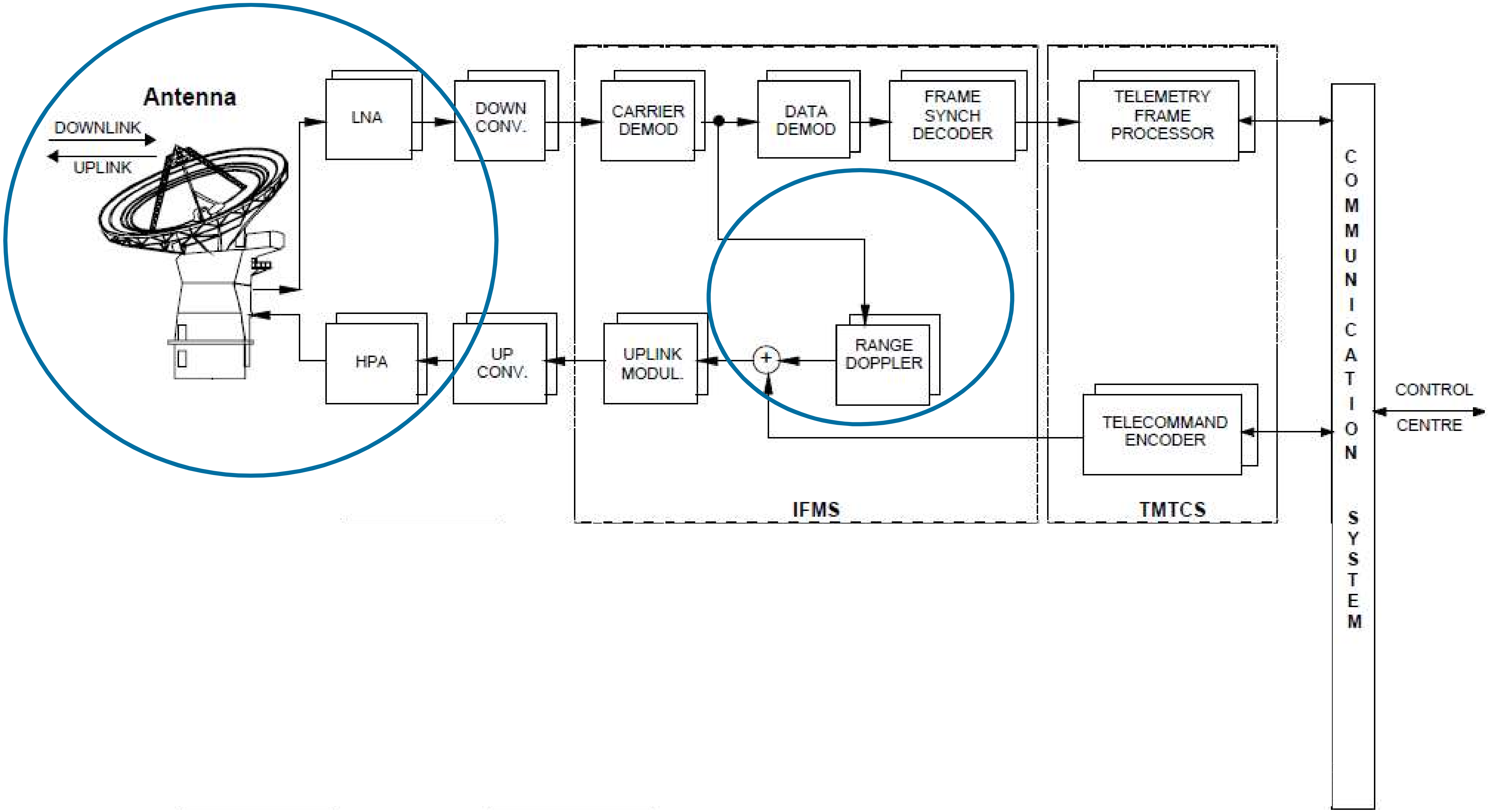
Objective:
To understand the impact of frequency and antenna choice
To quickly calculate important characteristics of your link with limited information
To understand the difference between the real situation and the textbook calculation

1. Antennas and scale
2. Antennas, frequency choice and beamwidth
3. Why ERIP is a really useful number and how to calculate it
4. Power Flux Density and interference on the ground
5. The great free space path loss swindle
6. Tracking

Typical ESA ground station



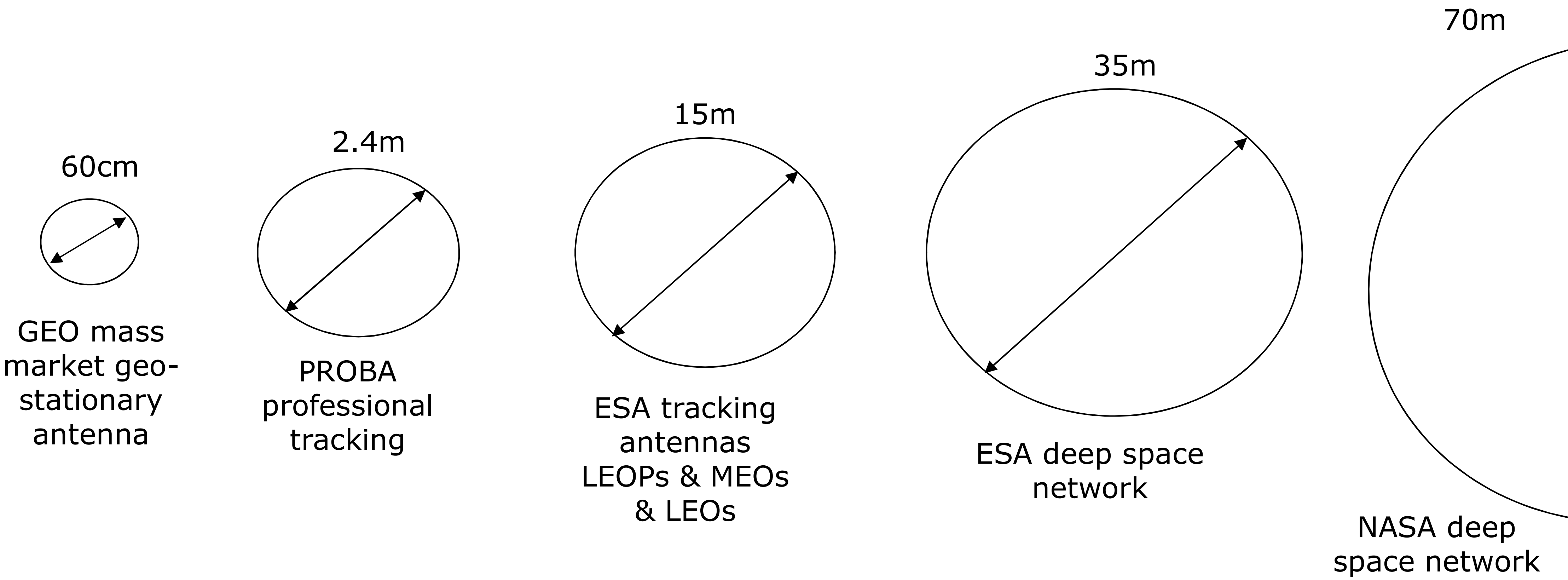
Have we missed anything?

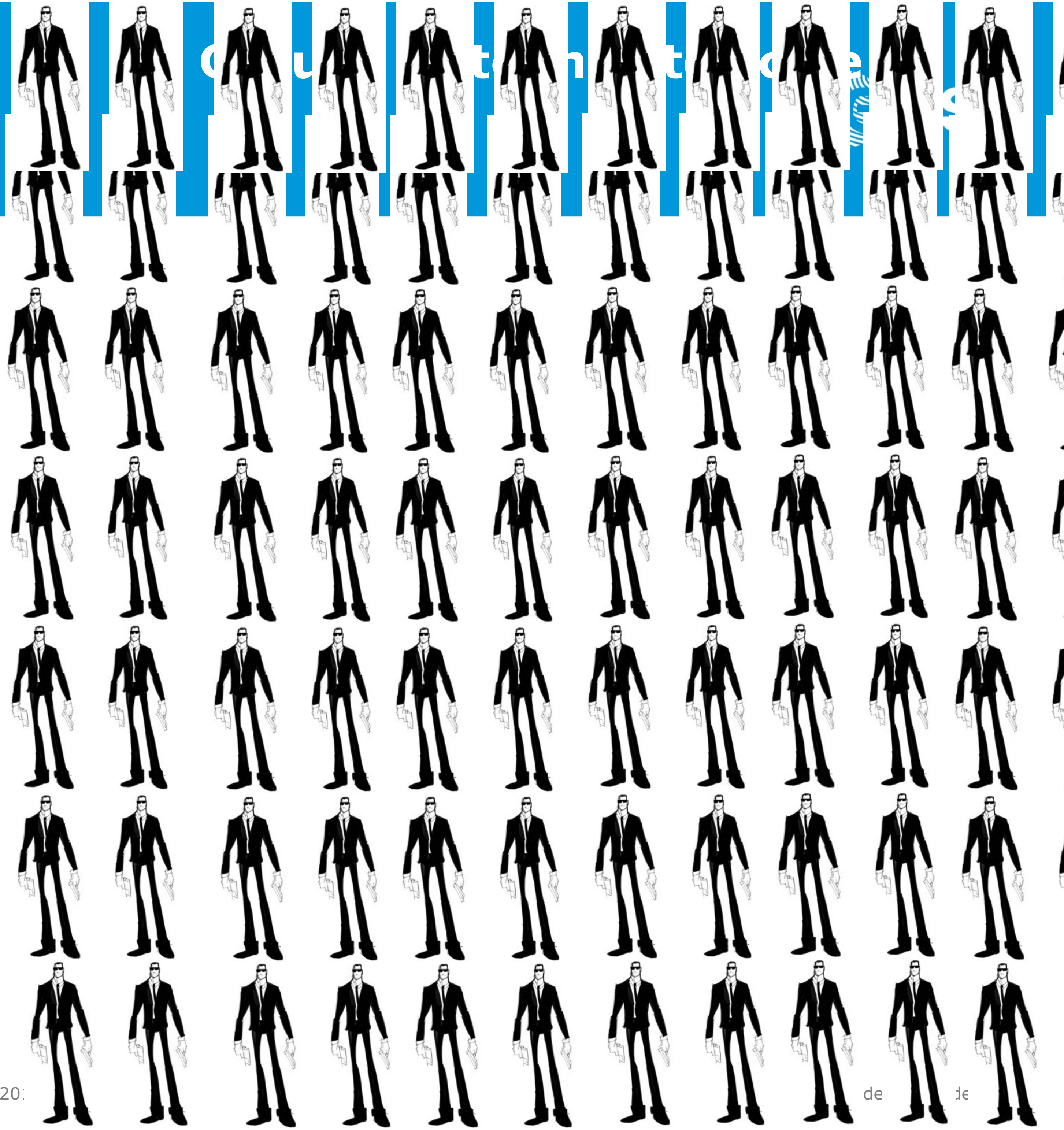


Some ESA antennas

Courtesy of Filippo Concaro, ESA/ESOC

Ground Station Antennas





15 m

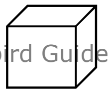
Size of four storey building

2 m

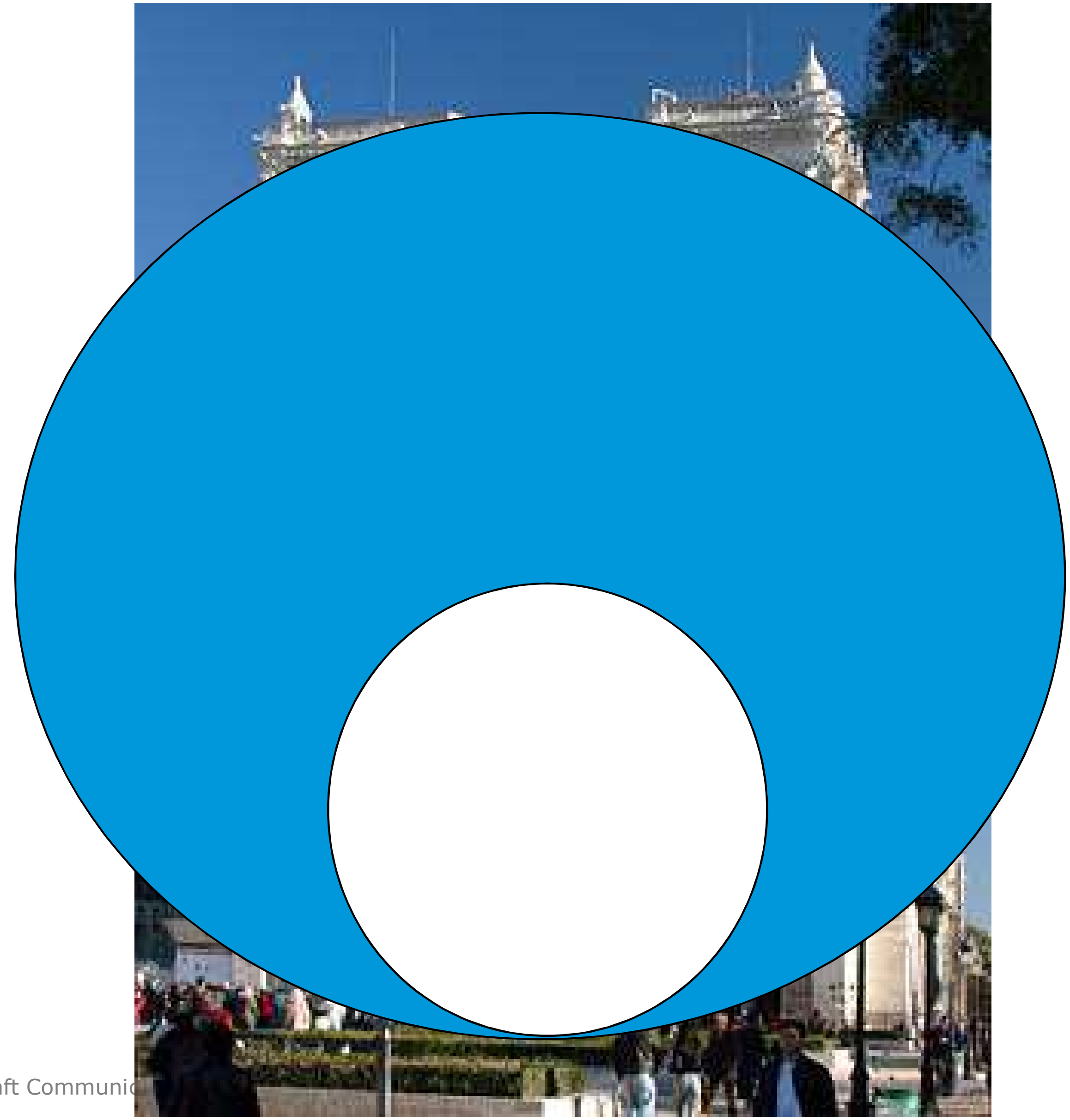
Two tall men

60cm

washing machine



Ground antennas to scale



Quiz: Guess how heavy in kgs is the dish of the 70 m NASA antenna at Goldstone?

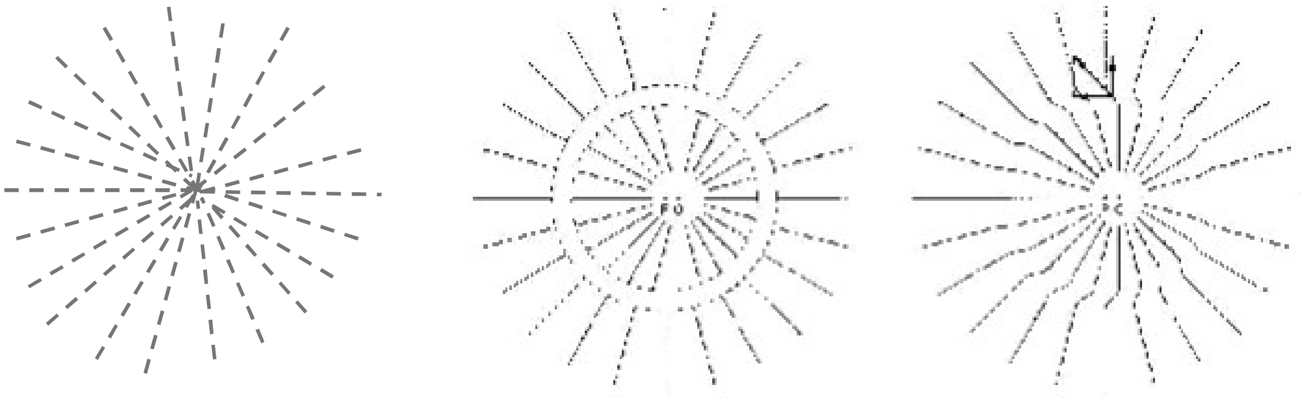
3 million kgs!

Recently had to lifted up to clean the bearings.

Latvia 2009

Feed

How do you create an electromagnetic wave from a voltage signal?



Amazing that getting such tiny things to move tiny distances can be used to communicate over hundreds of millions of kilometers!

The trick is to get them to move together…

Feed

QUIZ: How do we get the duck to move without touching it?

To make a strong EM wave we have to use resonance as well

Feed

The piece of equipment that makes the conversion from a voltage to a free flying electo-magnetic wave is called the feed.

It has to use resonance and therefore its physical size is often determined by the frequency of the wave it produces – just like tuning forks or organ pipes..

Once the waves are produced we can then concentrate them using reflectors.
These are then Medium and High Gain Antennas.

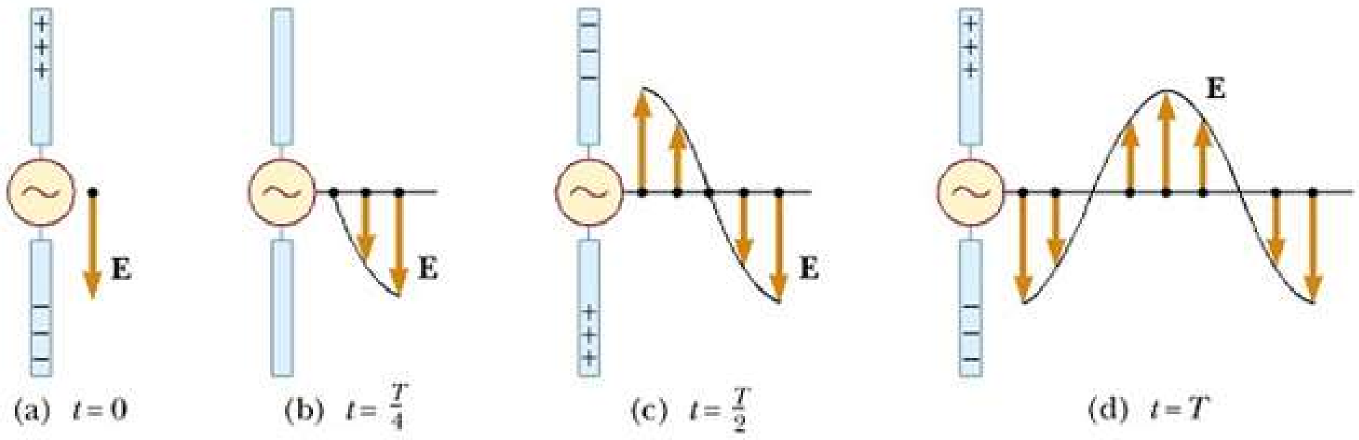
Or we can not use a reflector and let them radiate in all directions.
These are called Low gain antennas.

Low gain antennas are feeds without associated reflectors

Feed and Dipoles

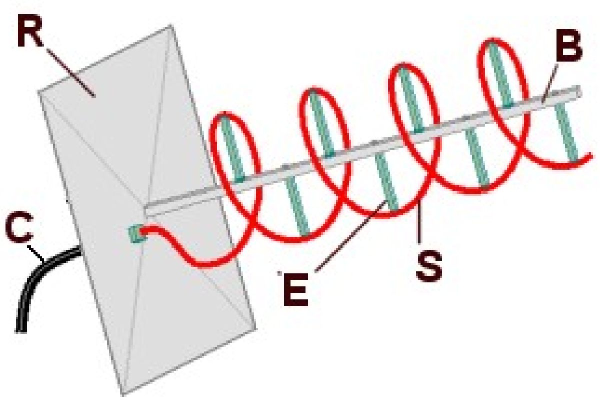
For LGAs their size is directly related to frequency

Dipole



Each branch a quarter-wavelength long for a omni directional antenna

Helix

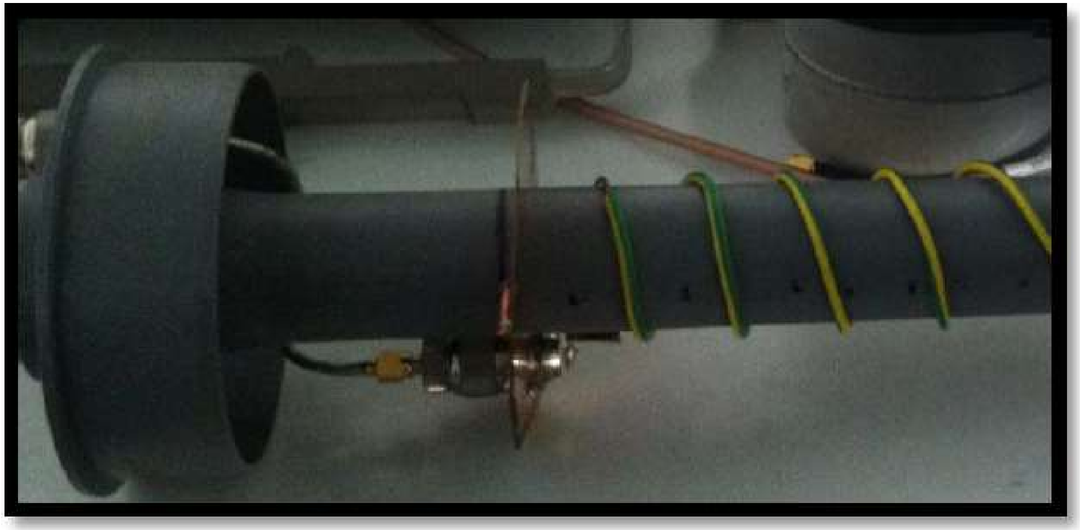


Shorter than a quarter-wavelength long for a omni directional antenna

Feed working in helical axial mode

In order to receive best performance of the antenna we were having two feeds for comparison, one bought from RF-Hamdesign and one self-build helical feed (constructed by B.Smeds):

A) Self-built feed - 13cm helical feed with 6 turns:



Left Hand Circular Polarization
Specification:
* Connector N-Female
* 50 ohm

Antennas: Reflector

The reflector is a physical structure and can be regarded as no different than your car headlight or a mirror

The size of the reflector is not directly related to the frequency.

QUIZ: What makes one antenna Ku band and another S band - besides the feed?

Antenna gain

Gain describes the ability of an antenna to direct that radiation in one direction.

The bigger the antenna dish the bigger the gain

For a reflector this can be explained in two ways:

1. From the reception point of view: the bigger the dish the greater the collection area
2. From the transmission point of view: The bigger the dish the greater the focus of the beam.

Antennas from the reception point of view

Large dish antennas that are many wavelengths across have a collection area roughly equal to their physical size.

Since dish area is $\pi r^2 = \frac{\pi d^2}{4}$ we can say gain $\propto$ dish diameter^2

The signal power the antenna will be able to deliver to the rest of the station is a function of the power left in the wave after its journey and this area

Receive power = Power in wave/m² x collection area x antenna efficiency

Receive power = Power in wave/m² x $\frac{\pi d^2}{4}$ x antenna efficiency

Antenna efficiency is just a measure of how well the antenna manages to capture that incoming power and channel it to the waveguide. It is usually between 55% and 70%.

Antennas from the transmission point of view

For transmission it is best to think of the antenna dish as a focusing mirror.

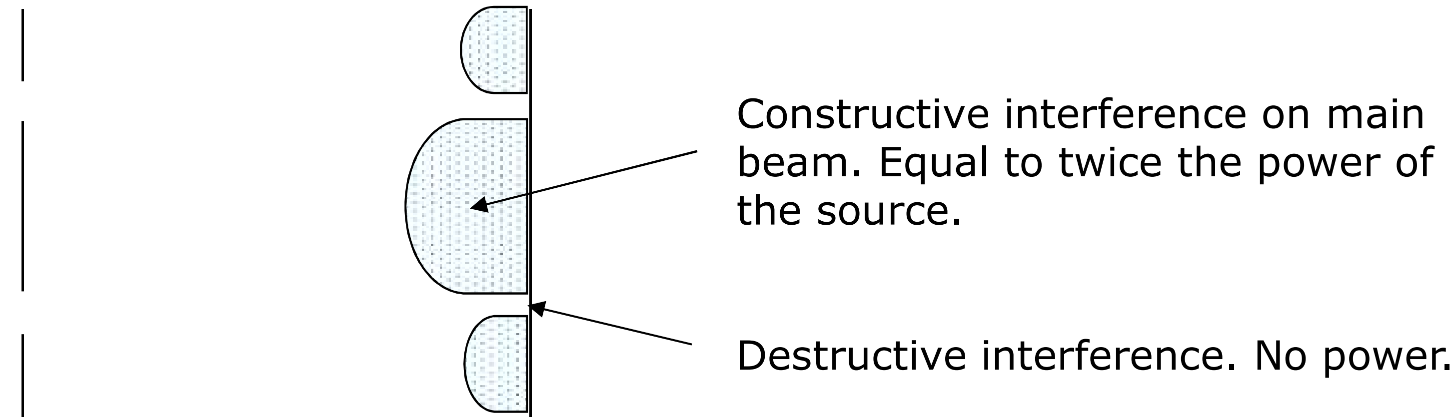
These focus the power of the signal in one direction, just like a car headlight.

The bigger they are the more they can focus.

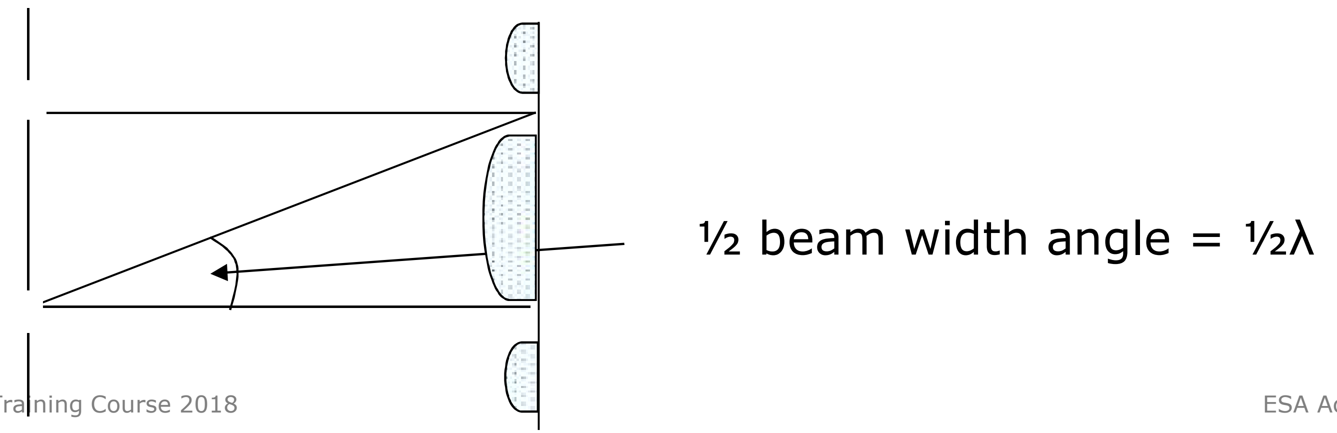
The bigger they are the smaller the beam.

Antenna gain and frequency

The second factor is wavelength of the signal. This is harder to explain but can be illustrated if we take a double slit as the simplest kind of directive antenna.

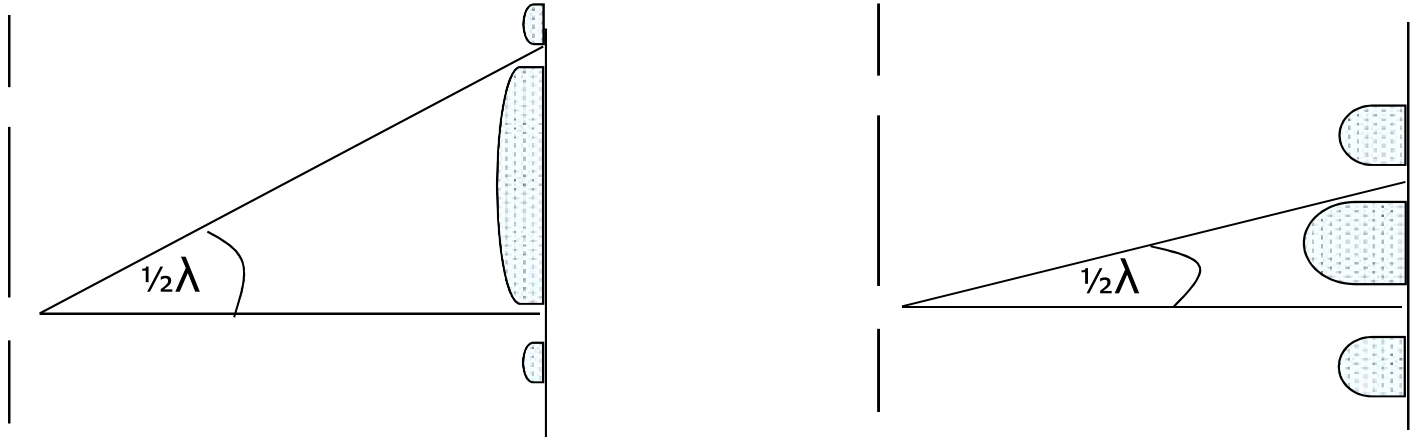


Now if we calculate the position of the destructive interference it will be where the two waves differ by half a wavelength and cancel out.



Antenna gain and frequency

From the following diagrams you can see that the smaller the wavelength the smaller the beam width angle.



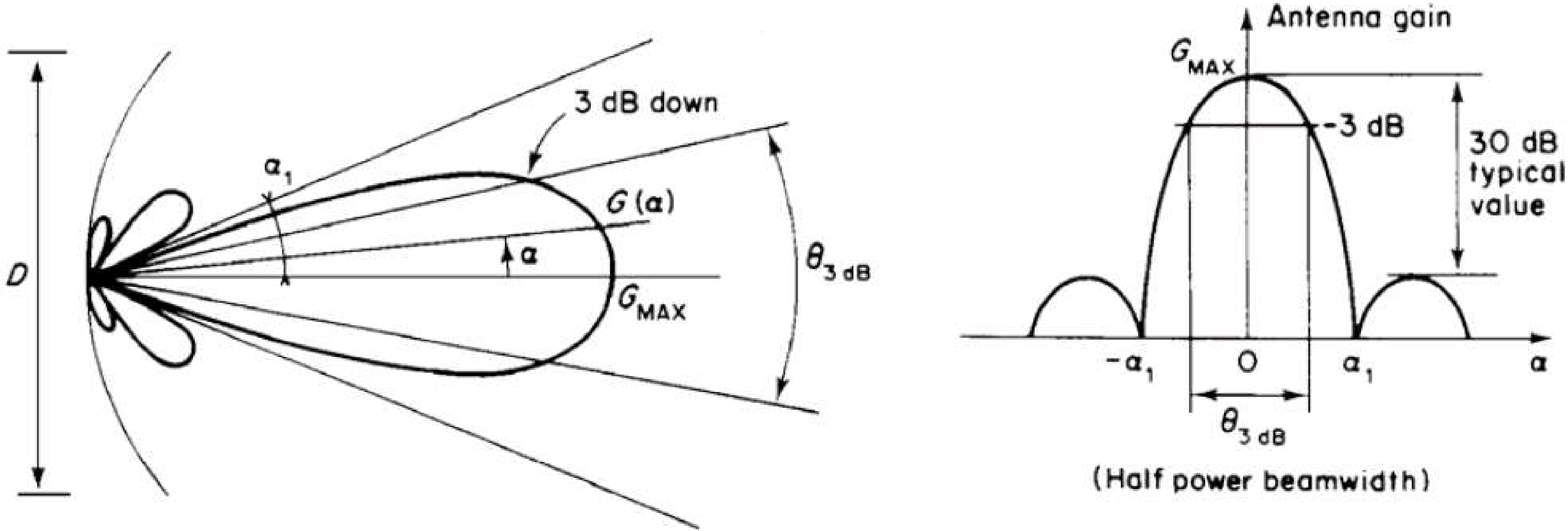
When this is expanded into two dimensions then we have a relationship of:

$$\text{gain} \propto \frac{1}{\text{wavelength}^2} \quad = \text{gain} \propto \text{frequency}^2$$

Therefore the higher the frequency the smaller the beam width and the greater the antenna gain. The effect can be dramatic.

QUIZ: How much more gain does an X band antenna have than an S band? X band is four times the frequency of S band.

Antenna Beamwidth



We define antenna beamwidth as the angle between which the signal stays at least 50% (-3dB) of maximum power.

A useful approximation is:

θ_{3dB} (degress) = illumination factor x λ/D (both in metres)

(illumination factor is somewhere 58 – 70 depending on the antenna type)

Summary

Antenna Gain $\propto$ frequency^2

Antenna Gain $\propto$ dish diameter^2

Antenna Gain is the amount of power radiated in one direction compared to an antenna that would radiate power equally in all directions (isotropic).

The result is given in dBi and is called *relative gain*.
Gain (dBi) = 10log (P/Pi)

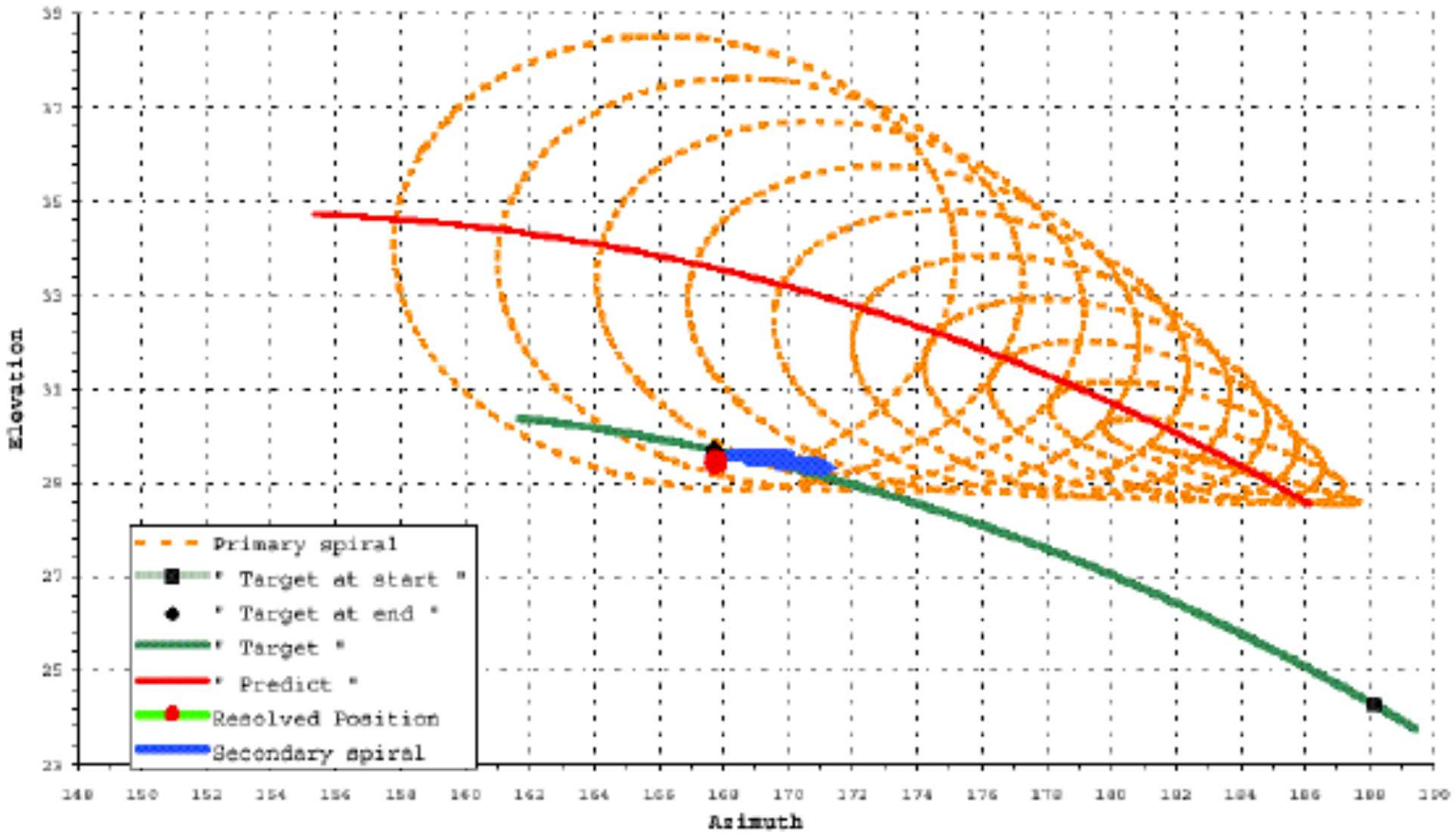
Gain (dBi) = $(\pi * D * f/c)^2$ * efficiency

Reception and transmission gain are the same

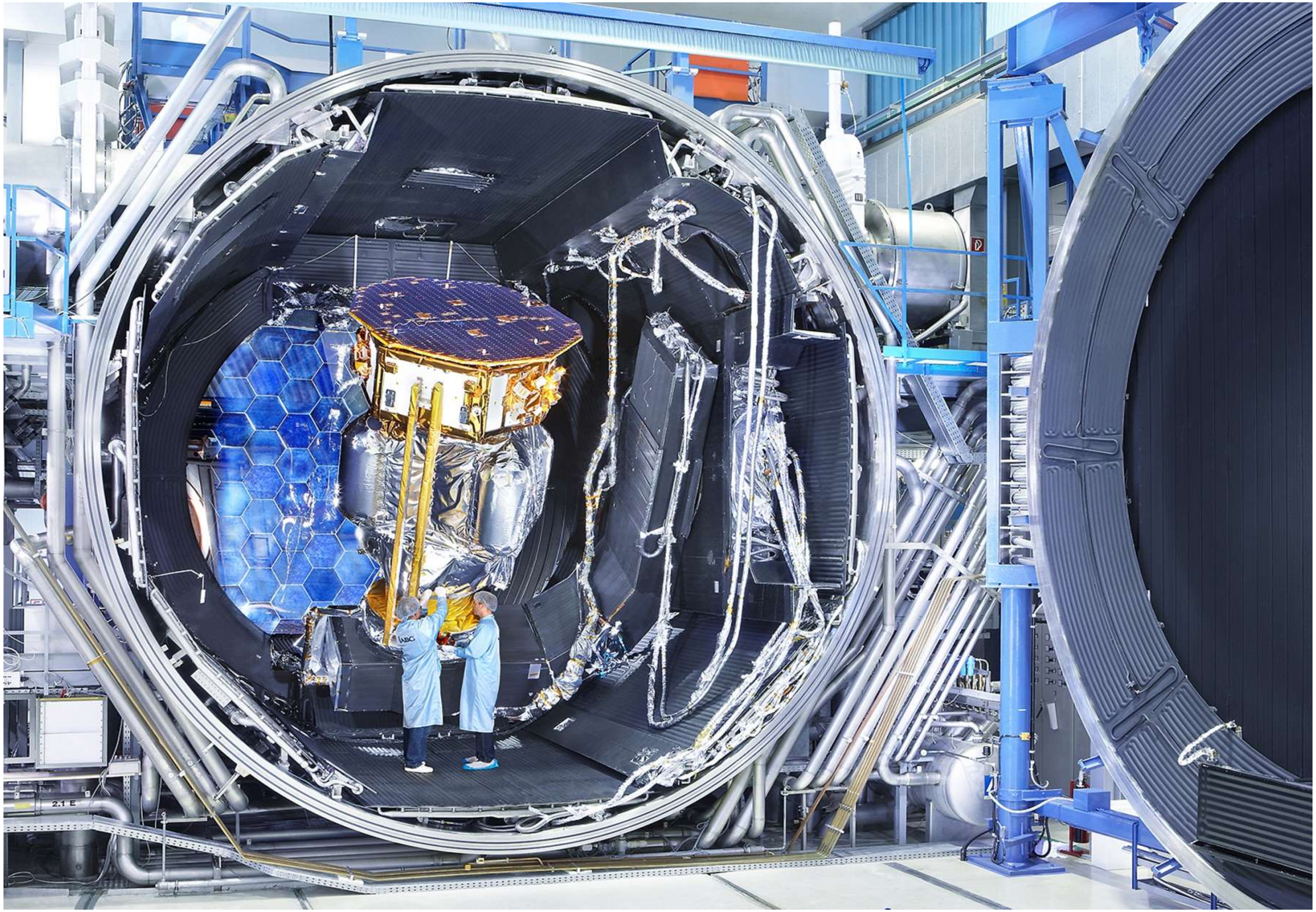
No free lunch!

Large antennas great for gain and antenna pointing accuracy in tracking mode (antenna pointing angles are used as an input to orbit determination)

Terrible in terms of cost and searching for lost satellites though….



Operational Experience: X band LEOP



Courtesy of Ian Harrison, ESA/ESOC

Operational Experience: X band LEOP

- X band 0.08deg beamwidth of 15m rather than 0.32deg in S-band

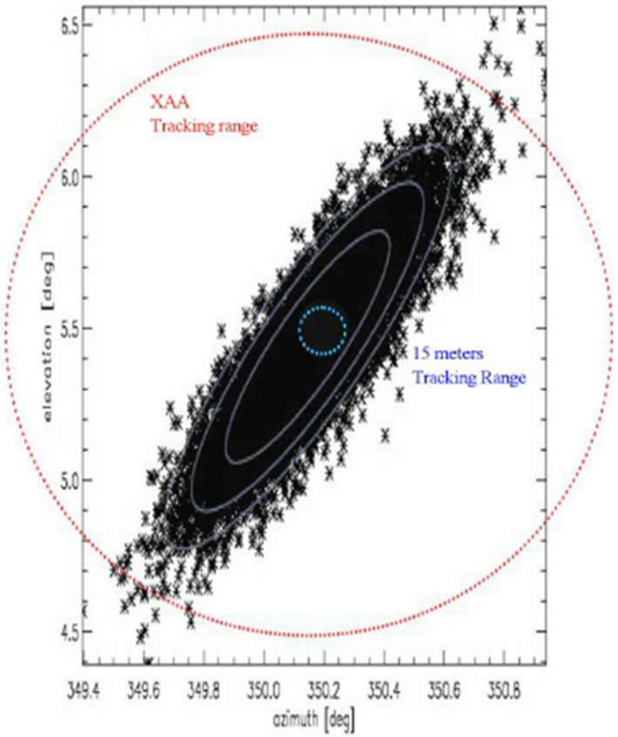


Figure 3-1 Comparison of tracking ranges for a 15 meters antenna and XAA (1.2 meters antenna). A typical 3σ dispersion area of Lisa Pathfinder is shown on the background [11]

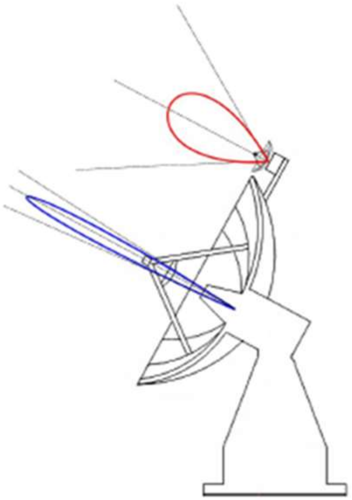
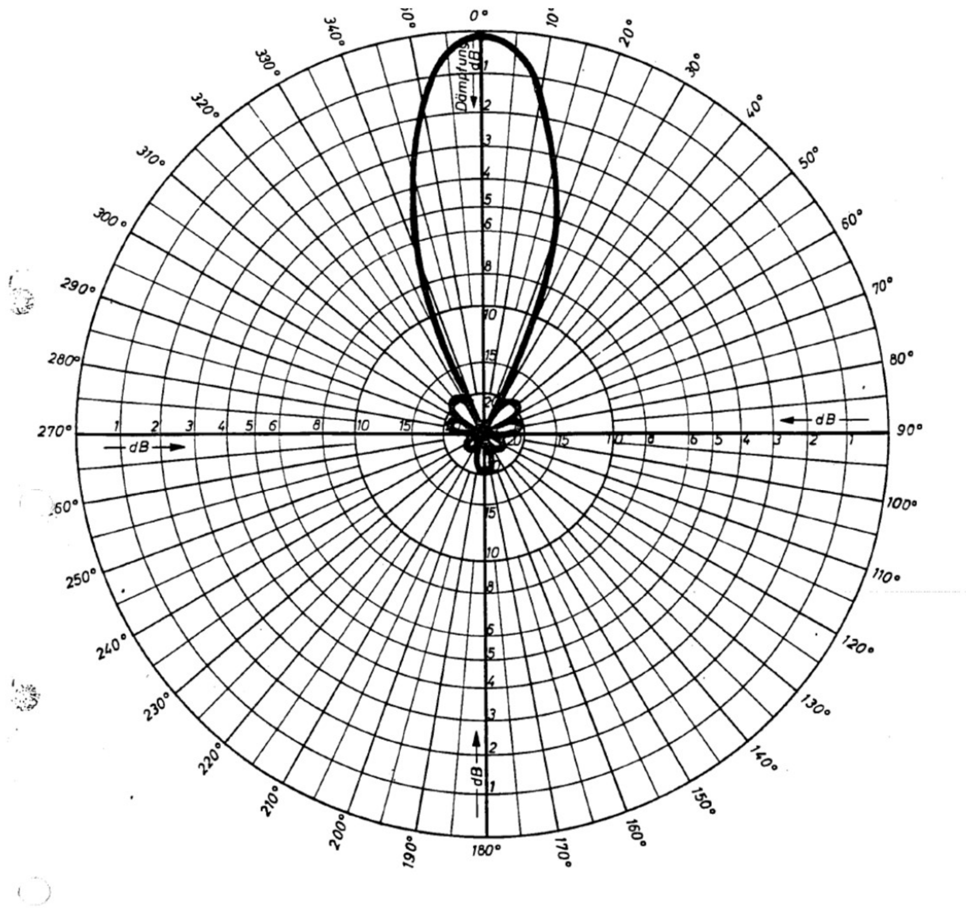


Figure 3-2 Graphical representation of the different antenna beams[2].

Courtesy of Ian Harrison, Filippo Concaro, ESA/ESOC

Equivalent Isotropical Radiated Power



To make things easy for ourselves later we convert everything to an easy to calculate situation i.e. an antenna producing a pattern that is an every increasing sphere.

Equivalent Isotropical Radiated Power

We can use relative gain to work out the

Equivalent Isotropical Radiated Power

For an ideal antenna (and quick calculation) we can just say

EIRP = TX power x Gain

This is really easy, e.g. for a transmit power of 20W and gain of 35 dBi

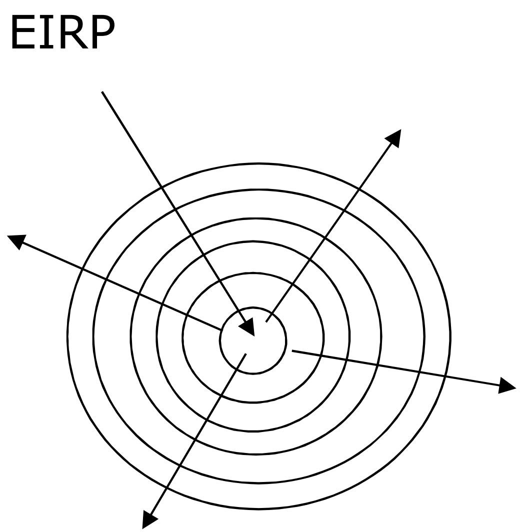
EIRP = 10log20 (i.e. 13 dBW) + 35 dBi = 48 dBW.

However to be more precise we should take into account all the losses in the transmit system

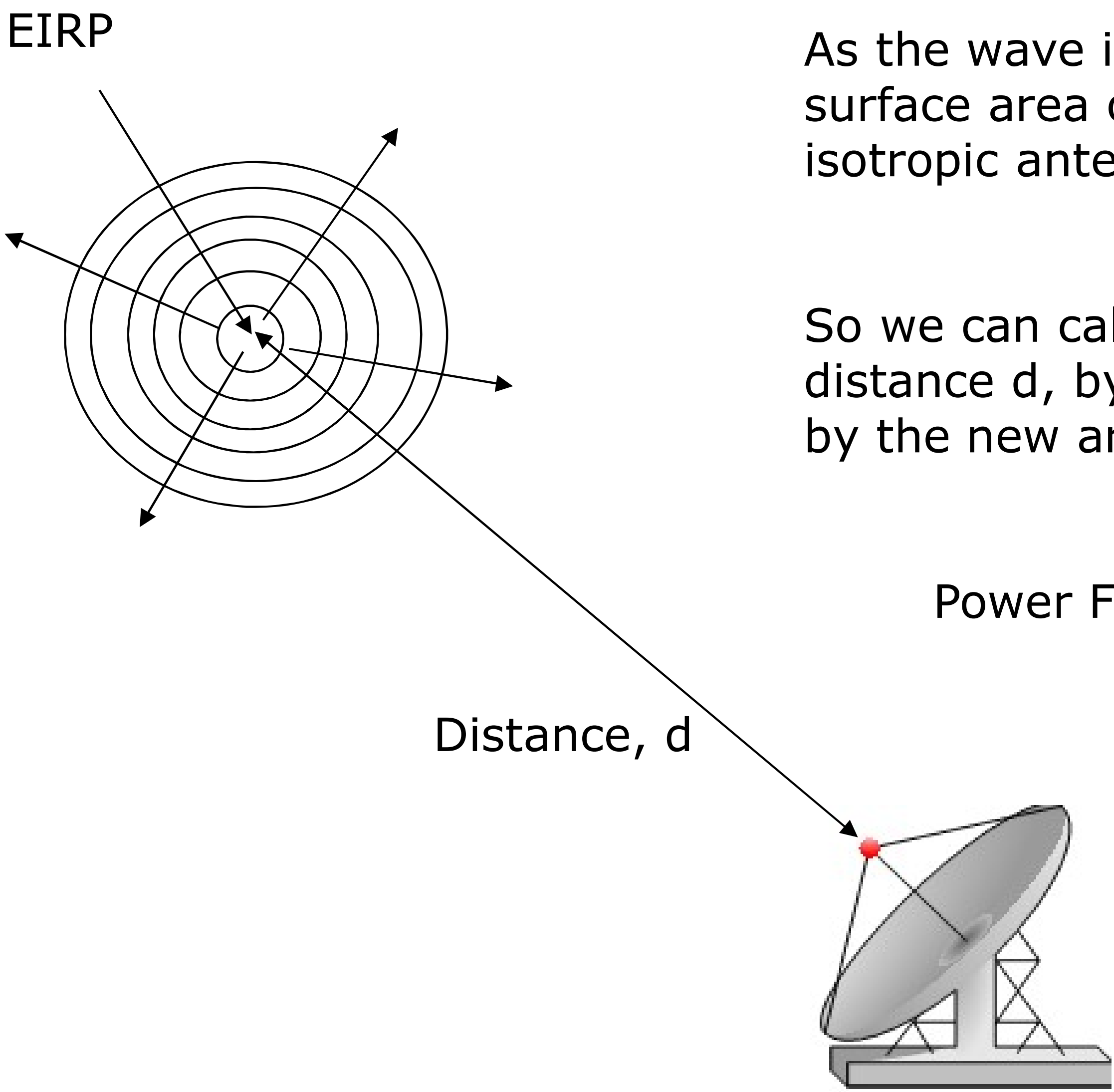
Why is EIRP useful?

From a distance you can treat this as a perfect isotropic antenna of that power radiating an ever expanding sphere!

It is easy to calculate the power of the incoming wave from an isotropic antenna when it hits the receive antenna.



Spreading Losses

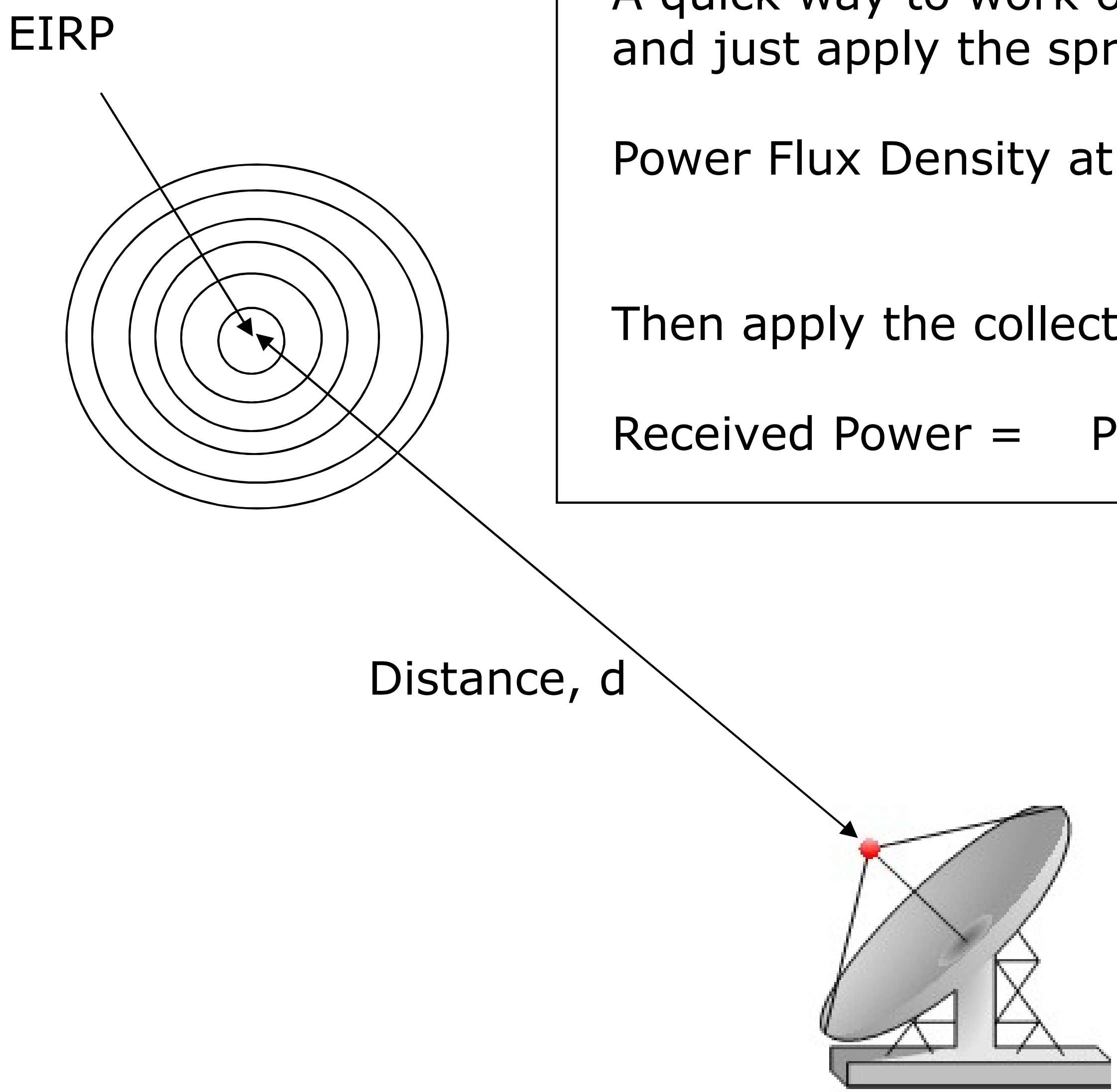


As the wave is expanding as a sphere it will have a surface area of $4\pi d^2$ at distance d (m) from the isotropic antenna.

So we can calculate the power flux density at distance d, by the simply dividing the initial power by the new area

$$\text{Power Flux Density at d (dBW/m}^2\text{)} = \frac{EIRP}{4\pi d^2}$$

Using this system to calculate received power



A quick way to work out the received power is to take the EIRP and just apply the spreading loss i.e. inverse square law:

$$\text{Power Flux Density at } d = \frac{\text{EIRP}}{4\pi d^2}$$

Then apply the collecting area idea to this incoming flux

Received Power = PFD x physical antenna area x efficiency

Energy per bit estimation

Recap: we want to make sure that the energy per bit / noise density ratio is enough for the BER and coding scheme selected.

We can already make an estimation for the energy per bit!

$$\text{Power for each bit} = \frac{\text{Received Power}}{\text{information rate}}$$

Wait a minute!

Free Space Path Loss is defined in every text book as

$$\text{FSPL} = \left(\frac{4\pi d}{\lambda}\right)^2 = \left(\frac{4\pi d f}{c}\right)^2$$

We just calculated spreading loss as $(4\pi d^2)$

What is going on?

The great FSPL swindle

QUIZ: Do higher frequency waves lose energy faste… an lower ones then?

> Transmission and Receiving Gain … are calculated with
>
> Gain (dBi) = (π * D *f/c)² …

WRONG

The frequency effect in the equation is only a convenient way to make calculations.

The great FSPL swindle

To understand why we need to look at antenna reception from the collection of wave power viewpoint again.

Large directive antennas (i.e. feed plus reflector) that are many wavelengths across have a collection area roughly equal to their physical size. Note the collection area has nothing to do with the frequency.

However small non-directive antennas (i.e. feed with no reflector) have physical dimensions that are completely governed by the frequency!

Collection area = $k\,(\lambda^2/4\pi) = k\,(1/4\pi(f/c)^2)$

Where k = 1 for an isotropic antenna, 1.5 for a dipole

Therefore the higher the frequency, the smaller the wavelength.

Hence the antenna must be smaller to work and it has a lower collection area and less receiving gain.

The great FSPL swindle

So the Free Space Path Loss includes the $4\pi(f/c)^2$ loss associated with the collection area of a Low Gain Antenna.

For a High Gain Antenna i.e. feed plus reflector there is no such loss! However we are also using a receiving gain that falsely increases for high frequencies in the receiving case.

<u>Therefore both lies cancel out</u>.

$$\mathrm{FSPL} = \left(\frac{4\pi d}{\lambda}\right)^2 = \left(\frac{4\pi d f}{c}\right)^2$$

Loss due to collection area of a LGA = $4\pi\left(\frac{f}{c}\right)^2$

When we remove this we end up with spreading loss again! i.e. $4\pi d^2$

Is high frequency best?

Let's do the following mind experiment.

1.)

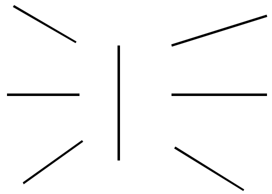
Two LGA communicating. The dipole size is determined by the frequency it can receive. The higher the frequency the shorter the wavelength, the smaller it must be and the less energy it can pick up.

According to k $(1/4\pi(f/c)^2)$ the *effective collecting area* of the dipole is decreased in proportion to the square of the frequency.

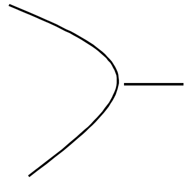
Looking at this the other way around the total loss of the system $\propto$ frequency^2

Is high frequency best?

2.)



LGA



directional antenna

<u>A LGA communicating with a directional antenna</u>

Increasing the frequency does not change the effective collecting area of the receiving antenna

Increasing the frequency does not change the gain of the transmitting antenna

Therefore the system is frequency independent

Is high frequency best?

3.)

Two directional antennas communicating

Increasing the frequency does not change the effective collecting area of the receiving antenna

Increasing the frequency decreases the beamwidth of the transmitting antenna as it focuses better in proportion to frequency^2. Therefore the wave the receiving antenna picks up has more energy per area than before.

The total system therefore gains in proportion to the frequency^2.

Which frequency is the best?

Remember we have 2 antennas and free space loss if the antenna is directional we get an increase in gain proportional to the frequency but our free space loss also increases.

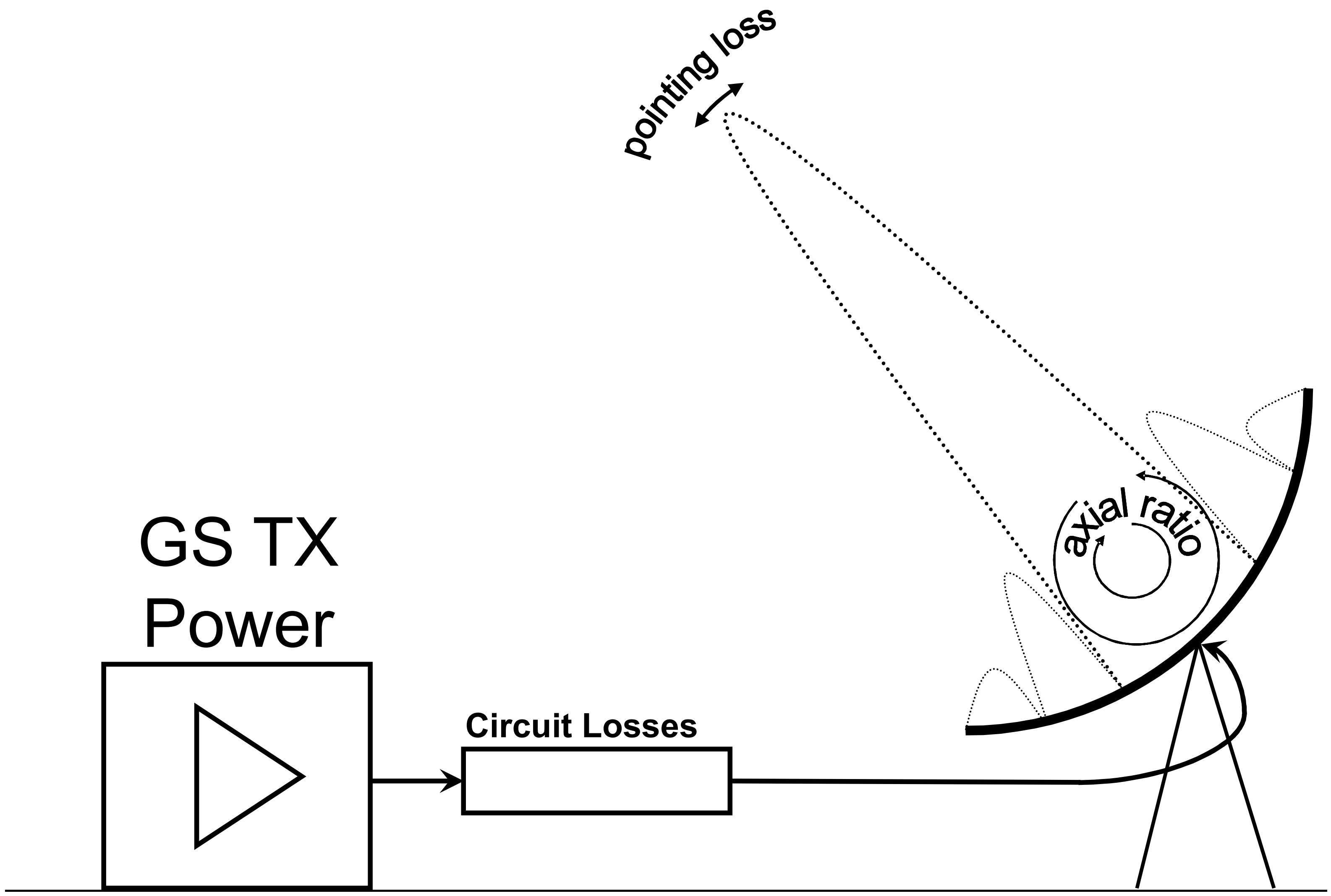
	Transmit	Free space loss	Recieve	Result
case 1)	LGA	$-(f^2)$	LGA	$-(f)^2$
case 2)	LGA	$-(f^2)$	f^2 (HGA)	0
case 3)	f^2 (HGA)	$-(f^2)$	LGA	0
case 4)	f^2 (HGA)	$-(f)^2$	f^2 (HGA)	$+(f)^2$

Therefore if you have non directional antennas on both receive and transmit the lower the frequency the better.

If one antenna is non directional the frequency makes no difference.

If both are directional though then the higher frequency is better.

Ground Station Transmission Losses



Ground Station Transmission Losses

- **G/S Antenna TX Axial Ratio**
  - This is a measure for the relation of the wanted versus the not wanted polarization. For space missions the polarization is right hand or left hand circular.
  - R = (1+Xa) / (Xa – 1), Xa is the amplitude ratio between intended and parasitic polarization
  - **Usually not important unless dual polarization link is used**
- **Pointing Loss [dB]**
  - Variations of the optimum pointing direction lead to amplitude variations at the receiver. The pointing error has to be much smaller than the beamwidth in order to avoid losses.
  - **Very small pointing losses for professional stations**
- **Circuit Loss [dB]**
  - Depends on how far the antenna is from the amplifier and

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

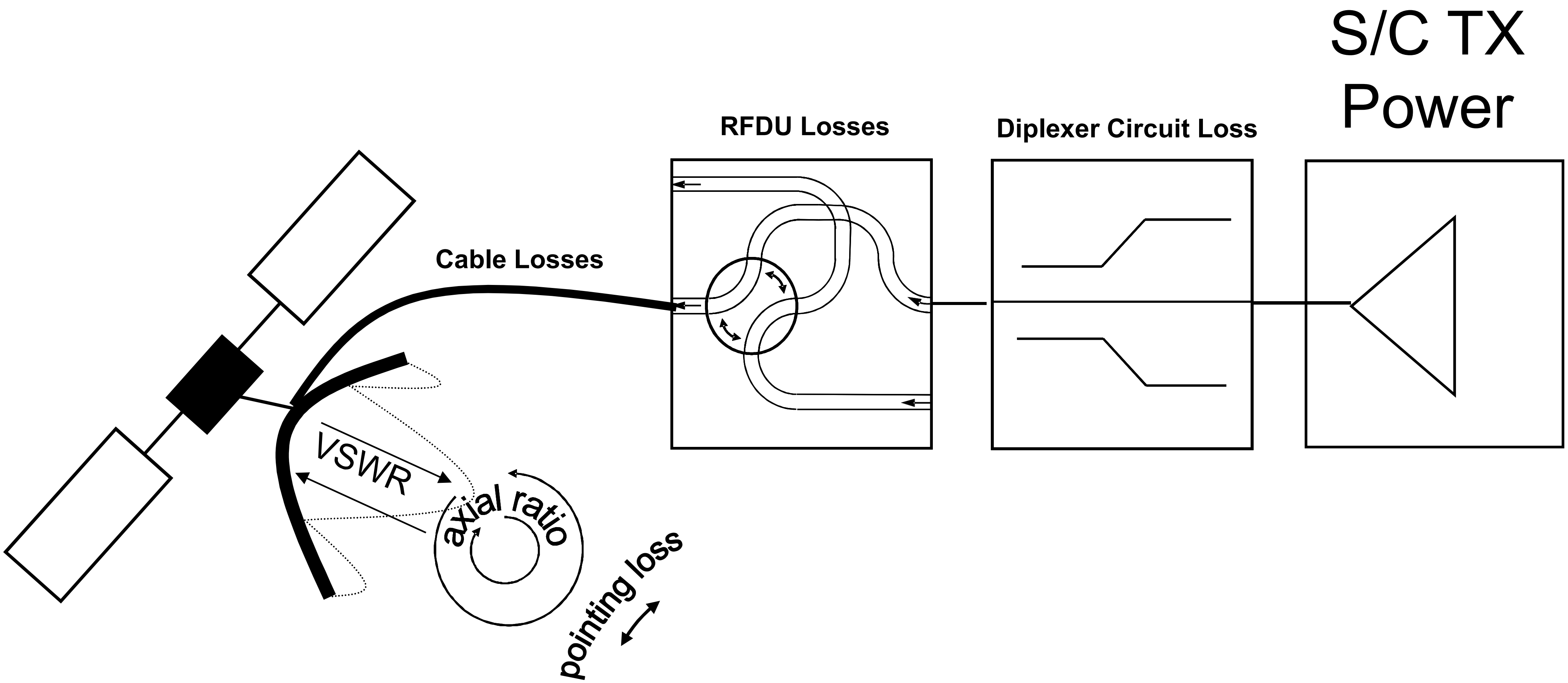
Adding dBs is like multiplying powers which is very useful later..

Ground Station Transmission: EIRP Calculation

+ TX Power [dBW]
- Circuit Loss [dB]
+ Gain [dBi]
- Pointing Loss [dB]
= EIRP [dBW]

Note: Polarisation losses are omitted here (can only be calculated by taking into account axial ratios of both antennas)

Spacecraft transmission losses



Note: Diplexers allow two different devices to share a common communications channel e.g. two transmitters to two antennas

Satellite Transmission: EIRP Calculation

\+ TX Power [dBW]
\- Diplexer Loss [dB]
\- RFDU Circuit Loss [dB]
\- Cable Loss [dB]
\- VSWR Loss [dB]
\+ Gain [dBi]
\- Pointing Loss [dB]
= EIRP [dBW]

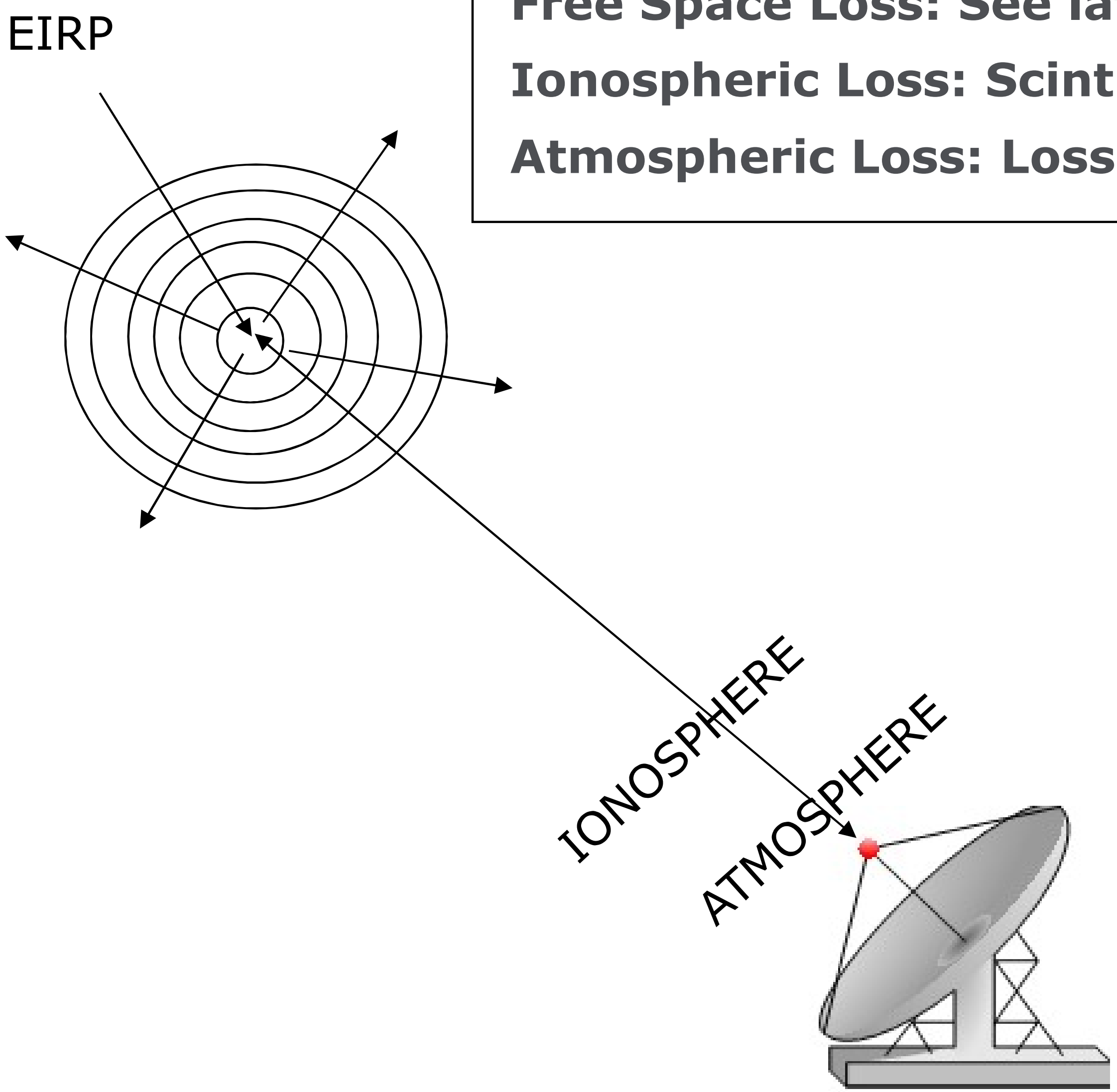
Note: Polarisation losses are omitted here (can only be calculated by taking into account axial ratios of both antennas)

Other Transmission Losses

Free Space Loss: See later

Ionospheric Loss: Scintillations caused by electrons

Atmospheric Loss: Losses in lower layers of troposphere



Propagation

- Free Space Path Loss (FSPL) = $((4\pi / c) * d * f)^2$

  Governing effect is the quadratic distance effect (signal power is distributed over an area that increases with the square of the distance)

- Ionospheric Loss

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

- Atmospheric loss is an issue for frequencies > 20 GHz (K-Band) (X-Band in heavy thunder storms and low elevations). Major absorbing medium is water (water vapour and rain).

Propagation Loss Calculation

+ Ionospheric loss [dB]
+ Atmospheric loss [dB]
+ Free Space Path loss [dB]
= Total propagation loss [dB]

Power Flux density

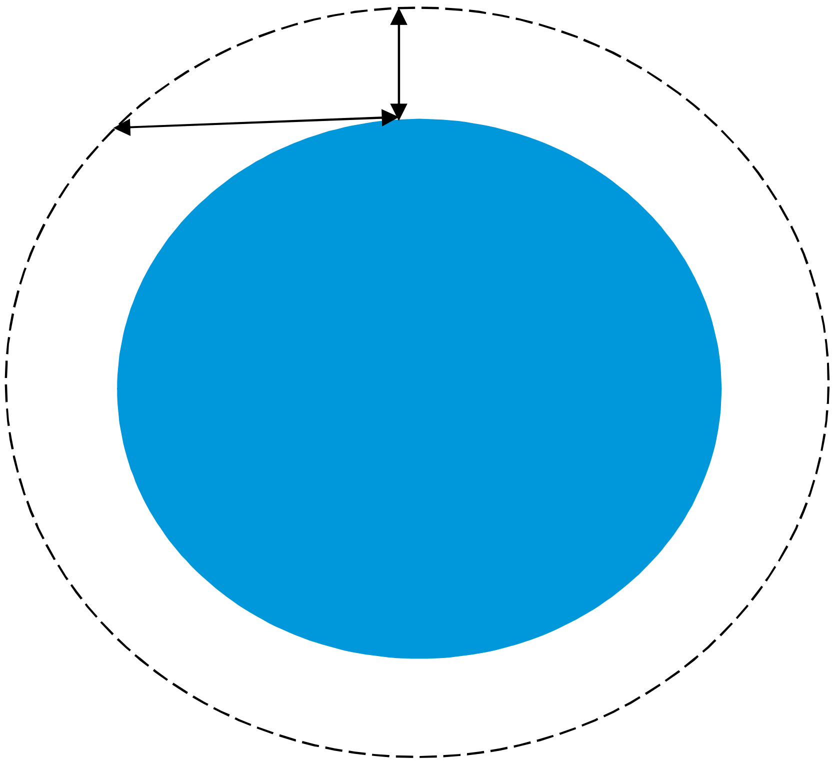
Power Flux Density is the amount of power reacting a unit area on the ground per wavelength. It is limited by the ITU to avoid interference with terrestrial systems.

You may be able to close the link by putting a better antenna on-board or more transmission power but this limit will ultimately block that route.

The limit is given within any 4 kHz band width, thus a modulation with residual carrier has more problems (as it has a peak).

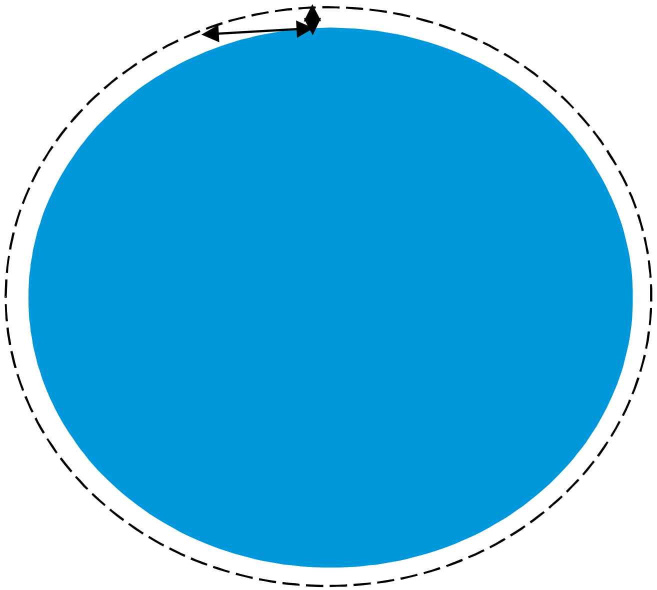
Watch out for geometry variations. You have calculate it for the worst case!

Variable geometry – slant range



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

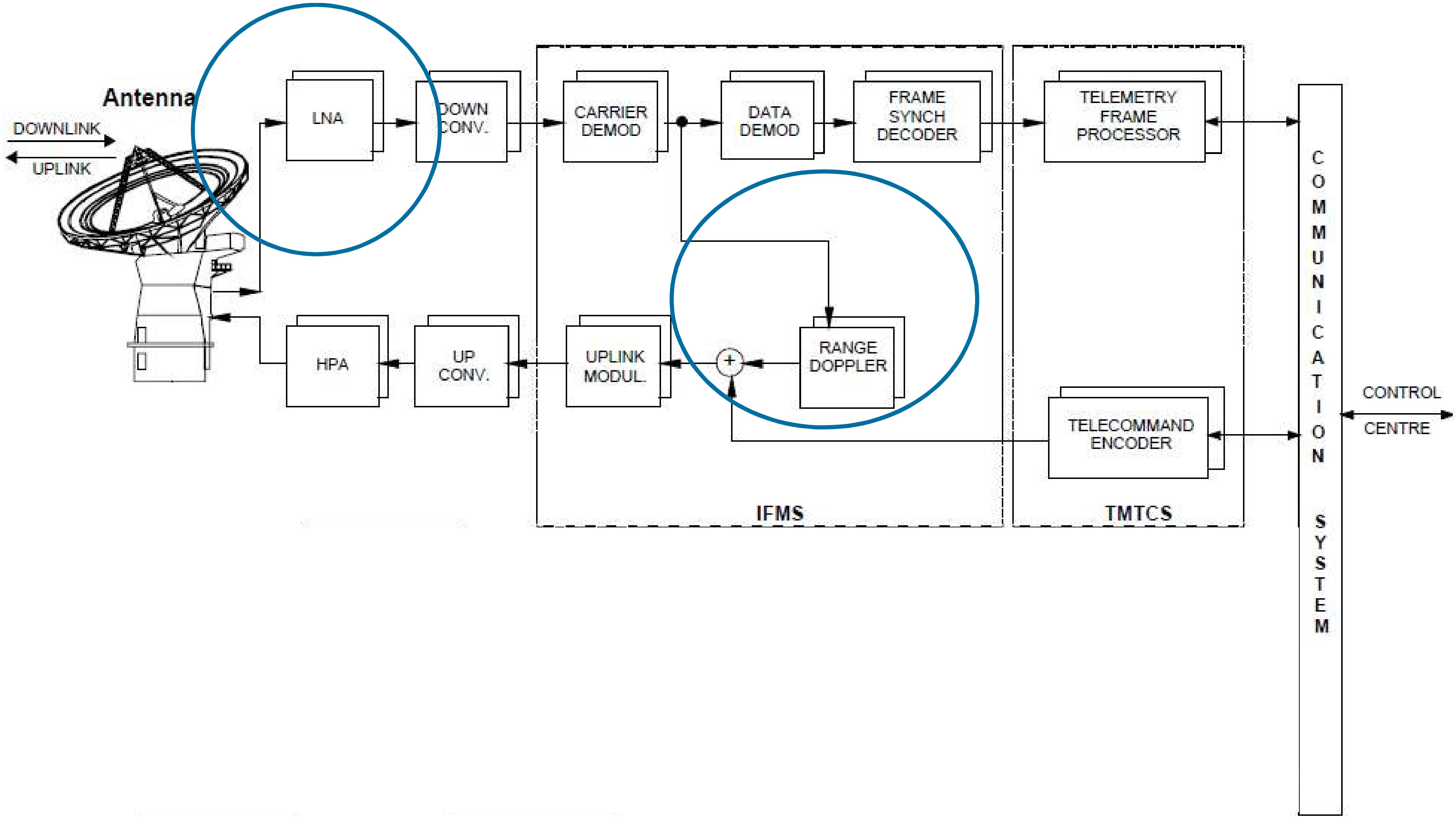
for a 800km orbit



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

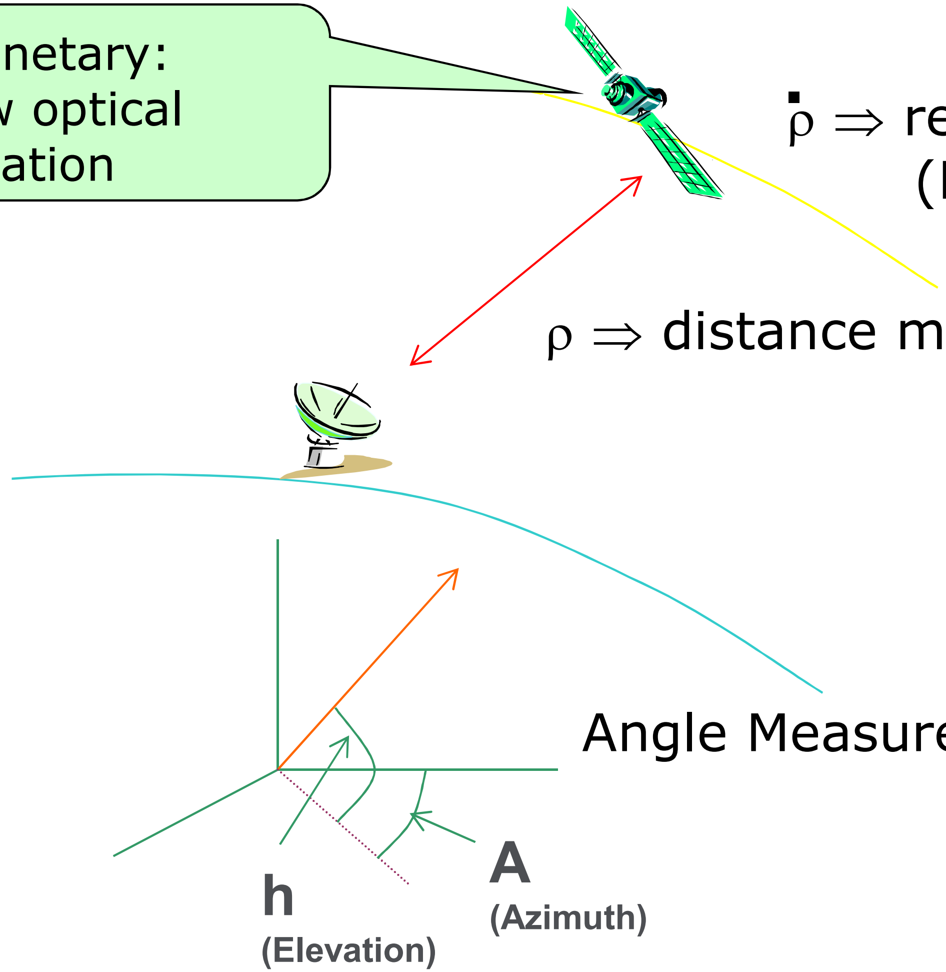
for a 300km orbit

Have we missed anything?



Ranging and Doppler

Interplanetary:
Also now optical
navigation

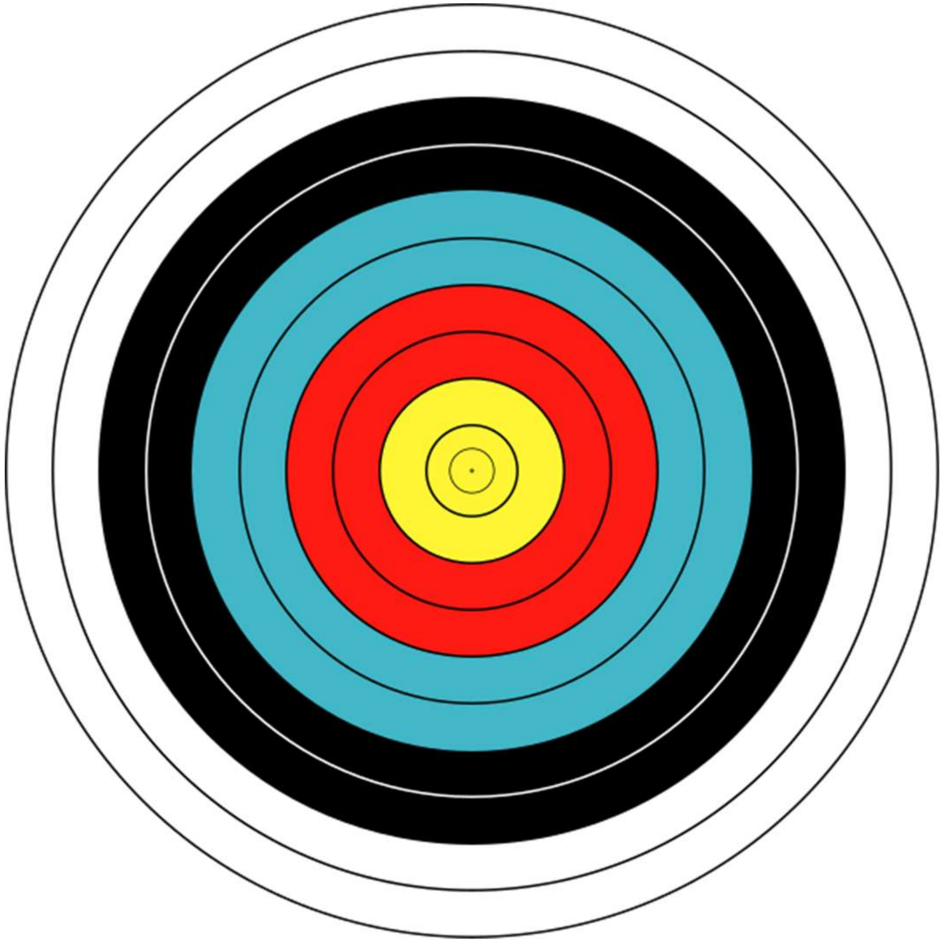


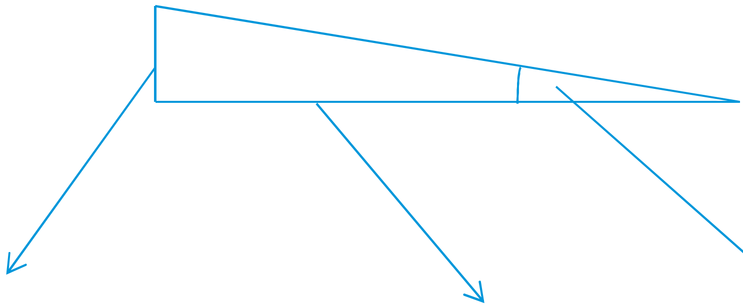
$\dot{\rho} \Rightarrow$ relative velocity measurement (Doppler)

$\rho \Rightarrow$ distance measurement (Ranging)

Angle Measurements (Auto-track)

A game

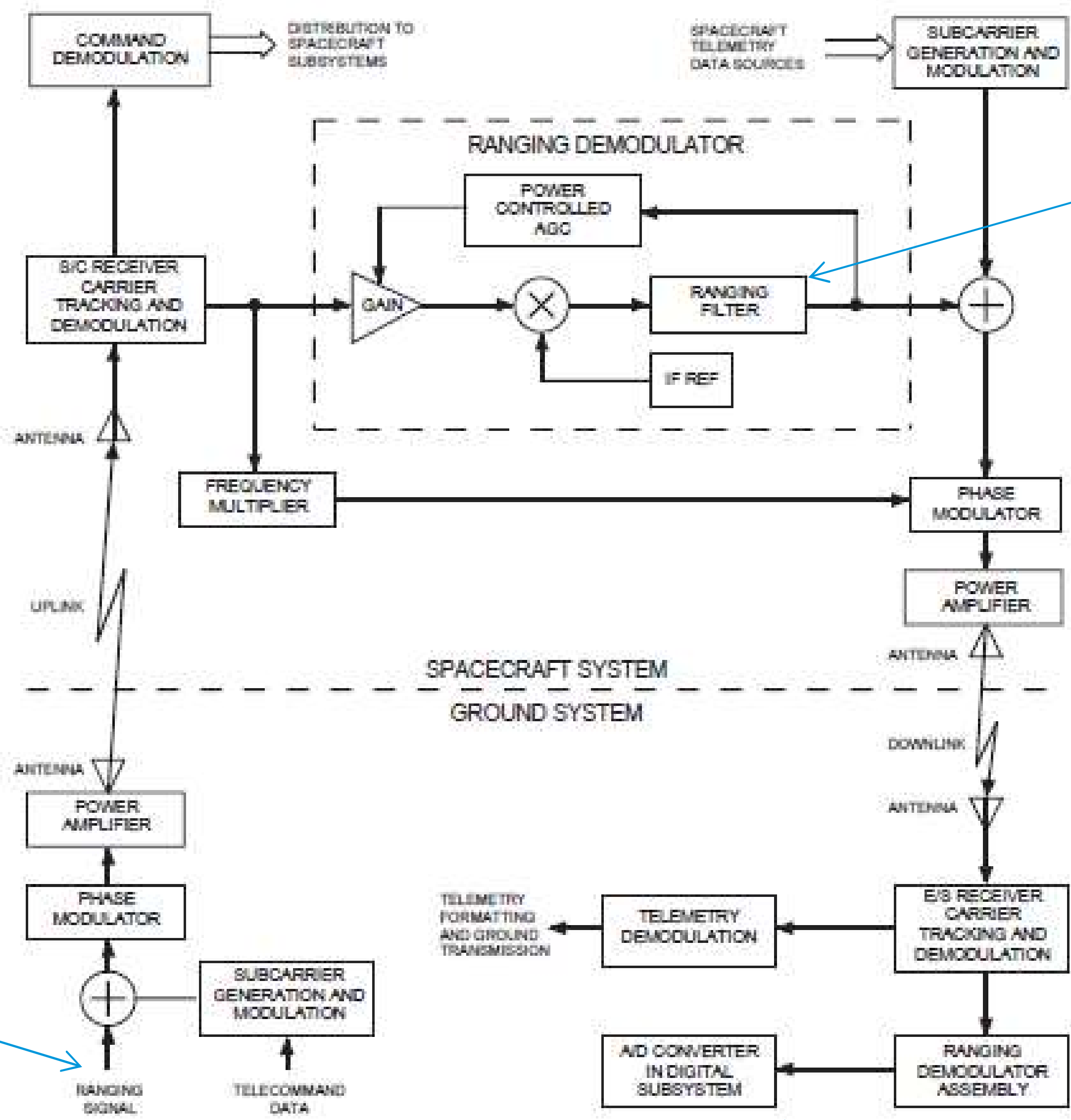




Out of Plane Error = Distance x sin(angular error)

We have enormous distances. Hence the problem is measuring the plane of sky position when tiny, tiny, tiny angle errors translate to enormous distance errors.

Ranging Signal – many subcarriers!



Filters the entire bandwidth in which the ranging signals can be present…. including all the noise!

Compares phase difference of transmitted and received signal to determine light time.

Ranging signal added as an extra subcarrier

Tone Ranging

Tone ranging is performed by adding different frequency subcarriers to the signal. Note this ranging does not work with supressed carrier schemes!

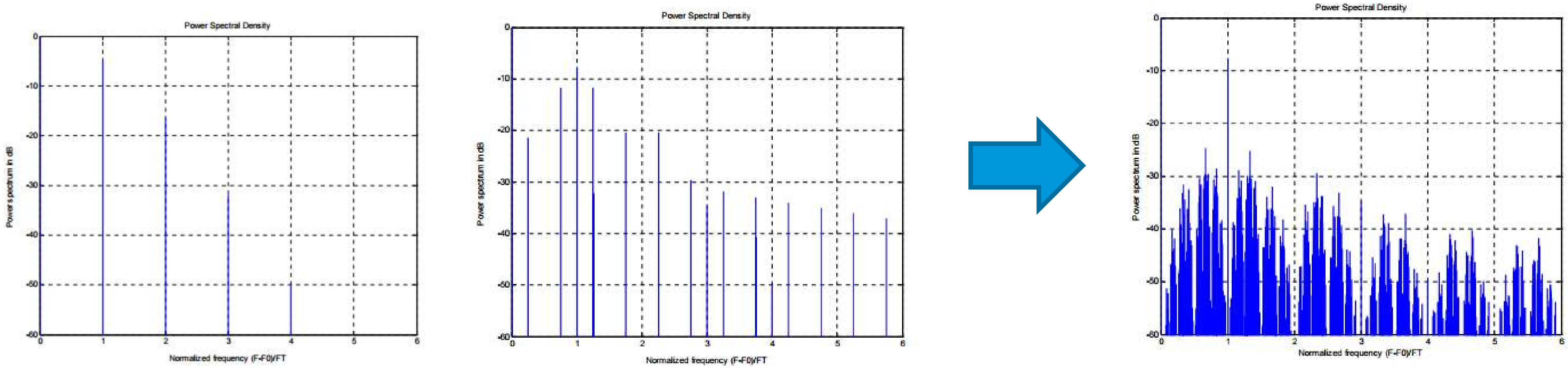
Just like residual carriers doing ranging takes power from the data signal. This needs to be accounted for in the link budget.

Just like residual carriers we need to choose the modulation index.

Note for uplink the bandwidth usage of ranging >> telecommand bandwidth usage.

For ranging to work the transponder does not need to be in coherent mode, see later.

Tone Ranging



Tone ranging works by measuring the phase difference between the sine wave modulated on the subcarrier and the received subcarrier. The higher the frequency the better the resolution BUT the harder it is to determine which cycle it is in.

The solution is to use several subcarriers of different frequencies to determine which cycle the highest frequency tone is in. This is called resolving the phase ambiguity.

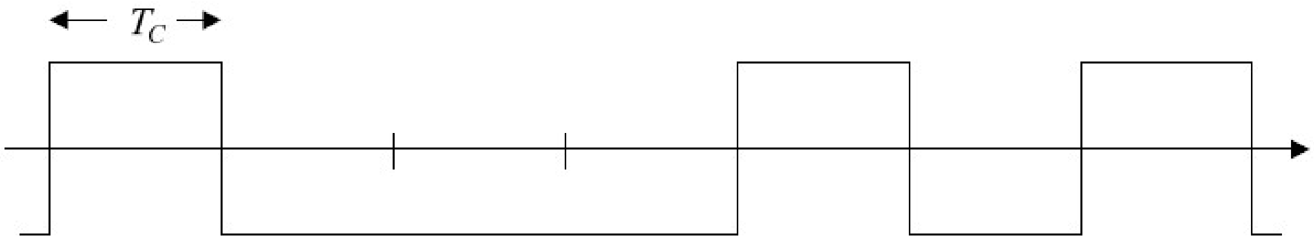
It can take a while to resolve ambiguity for deep space missions due to the light time (sometimes 20 minutes!).

Pseudo Noise Code ranging

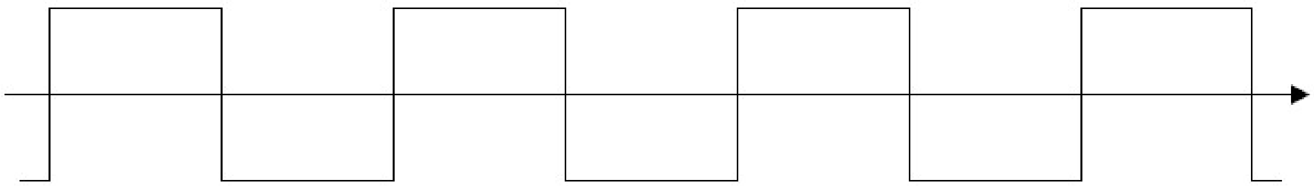
A system in which a periodic binary (±1) ranging sequence modulates an uplink carrier. This can be used in a simple turnaround (non-regenerative) manner or by detection, regeneration and retransmission to remove uplink noise.

Regenerative PN ranging provides such a substantial power advantage over non-regenerative ranging, up to 30 dB in proposed systems so perfect for deep space missions.

Bepi will be the first at ESA.

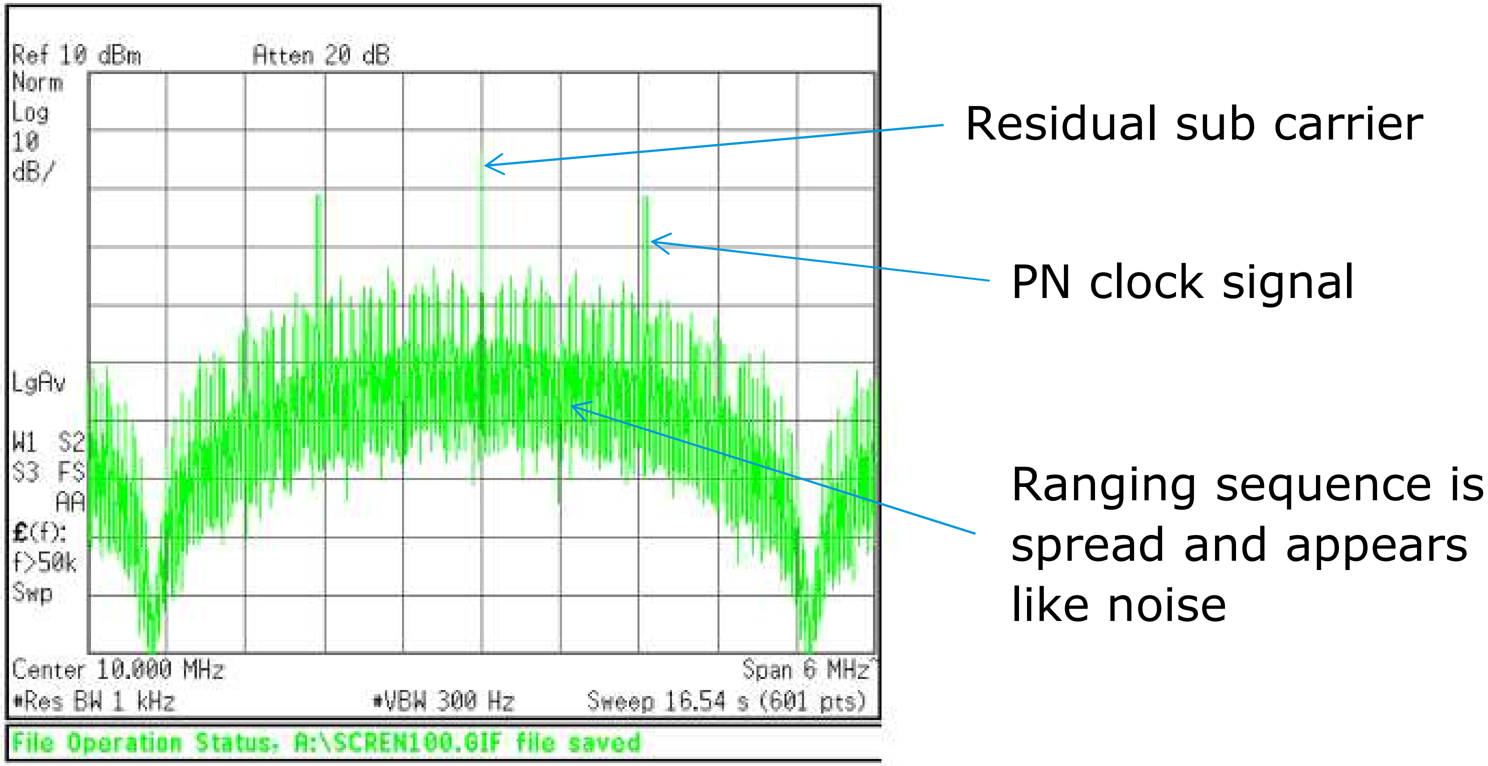


(a) ranging–sequence waveform



(b) range–clock waveform

Pseudo Noise Code ranging



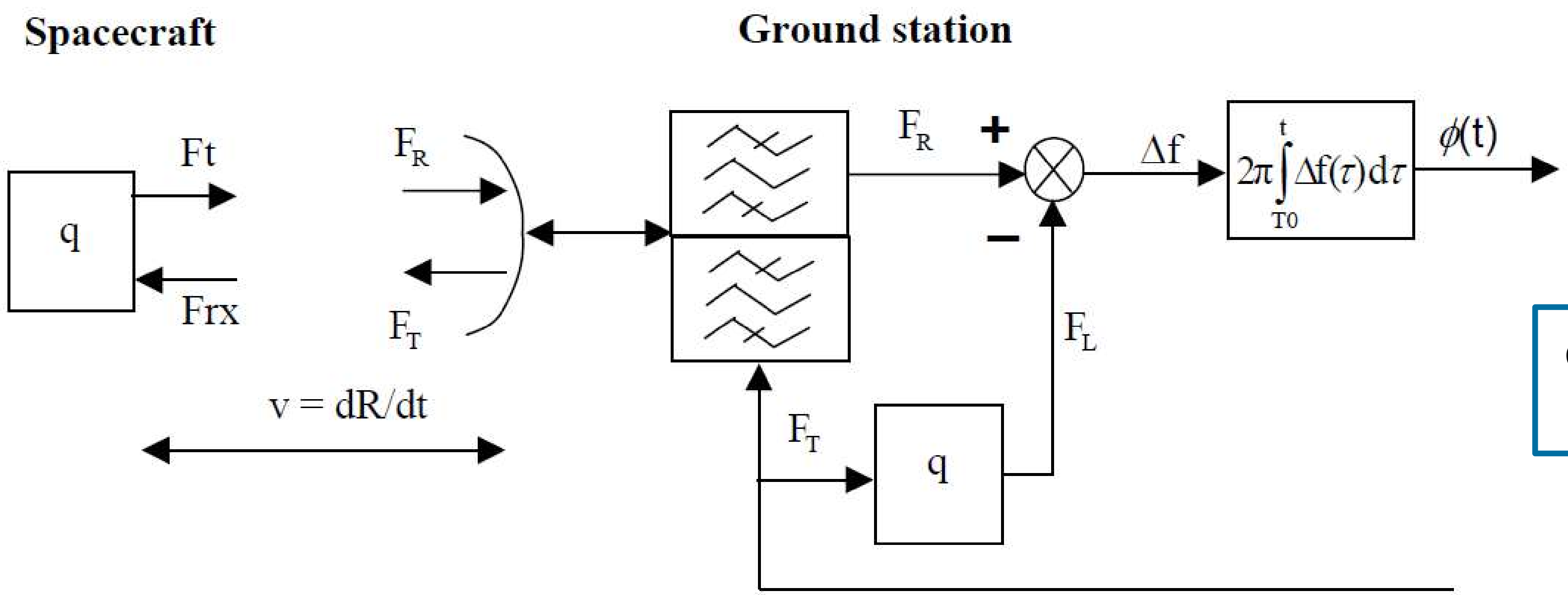
Still uses sub carriers so not compatible with suppressed carrier schemes.

A big advantage is that the use of long codes means that range ambiguity can be solved very fast (seconds). This is because multiple codes can be sent in parallel. So if TC lock is lost during a ranging session then it does not take a long time to restart.

Integrated Doppler

It is not an independent measurement of velocity but a series of continuous measurements of carrier phase difference evolution of the carrier over time.

One ends up with a time series of phase differences measured at 1 to 10 Hz.



q = turnaround ratio, see later

Measures the integrated phase difference of the regenerated carrier i.e. can be done with supressed carrier schemes and it does not take power from the data signal.

Usually done two way, coherent mode. Could be done in one-way non-coherent mode but the accuracy then depends on the stability of the on-board oscillator.

Coherent mode

Some ground systems use Doppler measurements to track the satellite and therefore to calculate its orbit.

Now if we want to measure the Doppler precisely we need the satellite transmitter to generate a very stable downlink frequency signal.

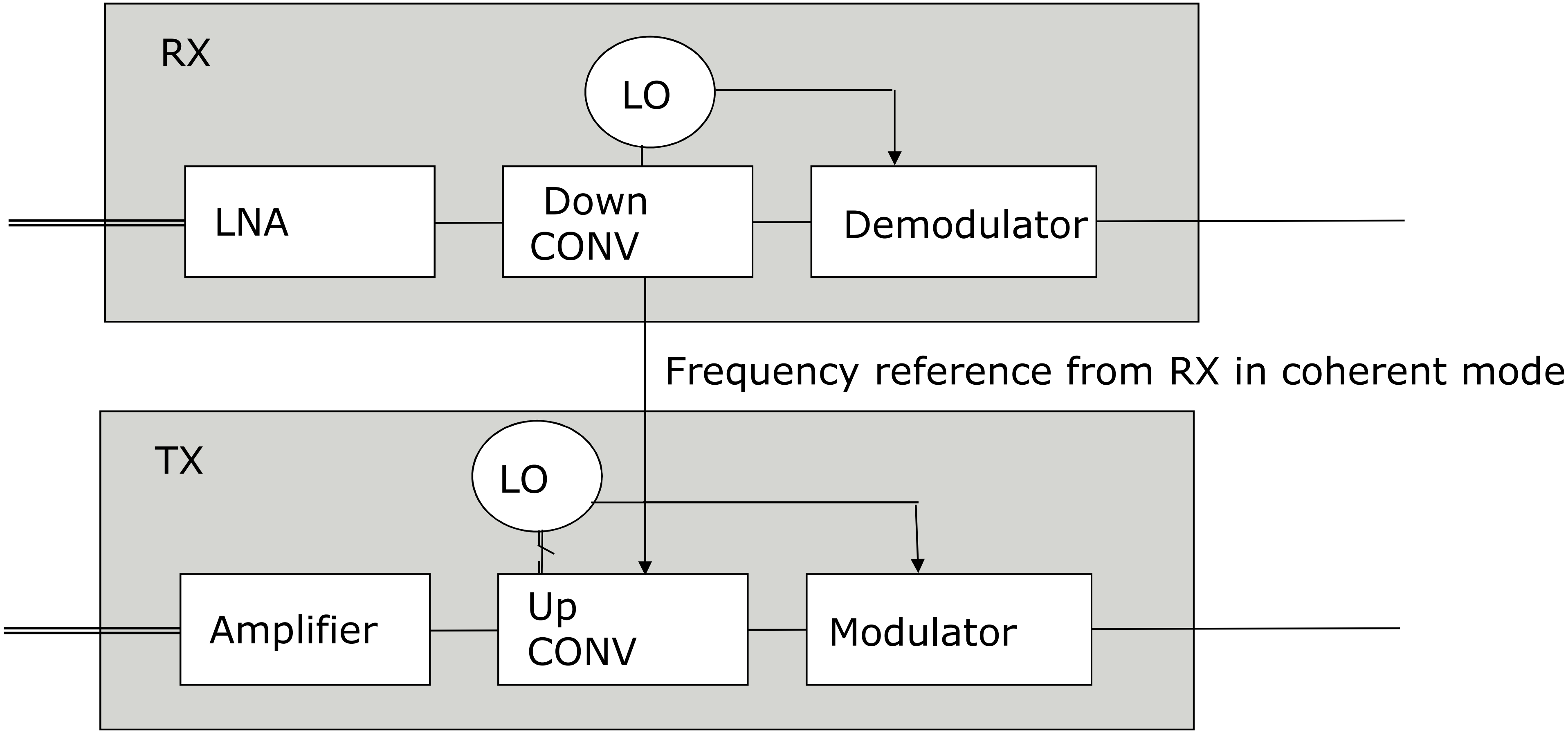
Otherwise the received signal frequency will jump around and we will not know what part of the jumps are caused by movement and which by the system noise.

Therefore the stability of the oscillator is a very important parameter of the transmitter. This is usually given in parts per million (ppm). Note it gets worse with age.

If we cannot afford an ultra stable oscillator on-board (too heavy, too expensive or just not good enough) then there is another option.

Coherent mode

We can generate a very stable signal on the ground and then the on-board transmitter uses this received frequency reference for it’s downlink signal.



Turnaround ratio

We cannot transmit the downlink on the same frequency as the uplink – otherwise they will interfere with each other.

A standard turnaround ratio is usually adopted. It is different depending on the frequency band used.

Frequency bands	Turn around ratio
S/S	221/240
S/X	221/880
X/X	749/880
X/S	749/240

It simply means the uplink divided by the downlink should be equal to this fraction.

Note in the same frequency band the uplink is always lower than the downlink.

Integrated Doppler and Deep Space

Note that if you measure integrated Doppler over a long period of time there will be another signal imprinted on the line of sight velocity of the spacecraft.

QUIZ: What signal is this?

QUIZ: What will it look like?

This sine wave shows the change in velocity and angle caused by the Earth's rotation. Luckily this is known and it can be used to calibrate the other measurements

This gives Flight Dynamics some information about the plane of sky information.

About 4 hours continuous data is required for such measurements to be useful and they are required over several days…

Operational Experience: Doppler

Envisat: launched 1 March 2002, Largest earth observation satellite ever launched – 8 tonnes.

Loss of contact 8 April 2012 now a major space debris risk.

Had an enormous LEOP network which has been unsurpassed.

During RFCTs at Wallops and Goddard, ESOC found out that the stations performed uplink sweeps by stepping the frequency whereas ESA stations continuously sweep.

Strange behavior was seen during the test. The uplink frequency remained stable but the downlink frequency started sweeping!

Anomaly board was set up and Alenia found that if the uplink moved from a negative to positive value through rest frequency it provoked a rounding error in the NCO (responsible for performing the turnaround function).

The impact would have been these stations would not be able lock in coherent mode and so the Doppler tracking would not work.

Courtesy of Kevin Kewin, ESA/ESOC

Operational Experience: Doppler

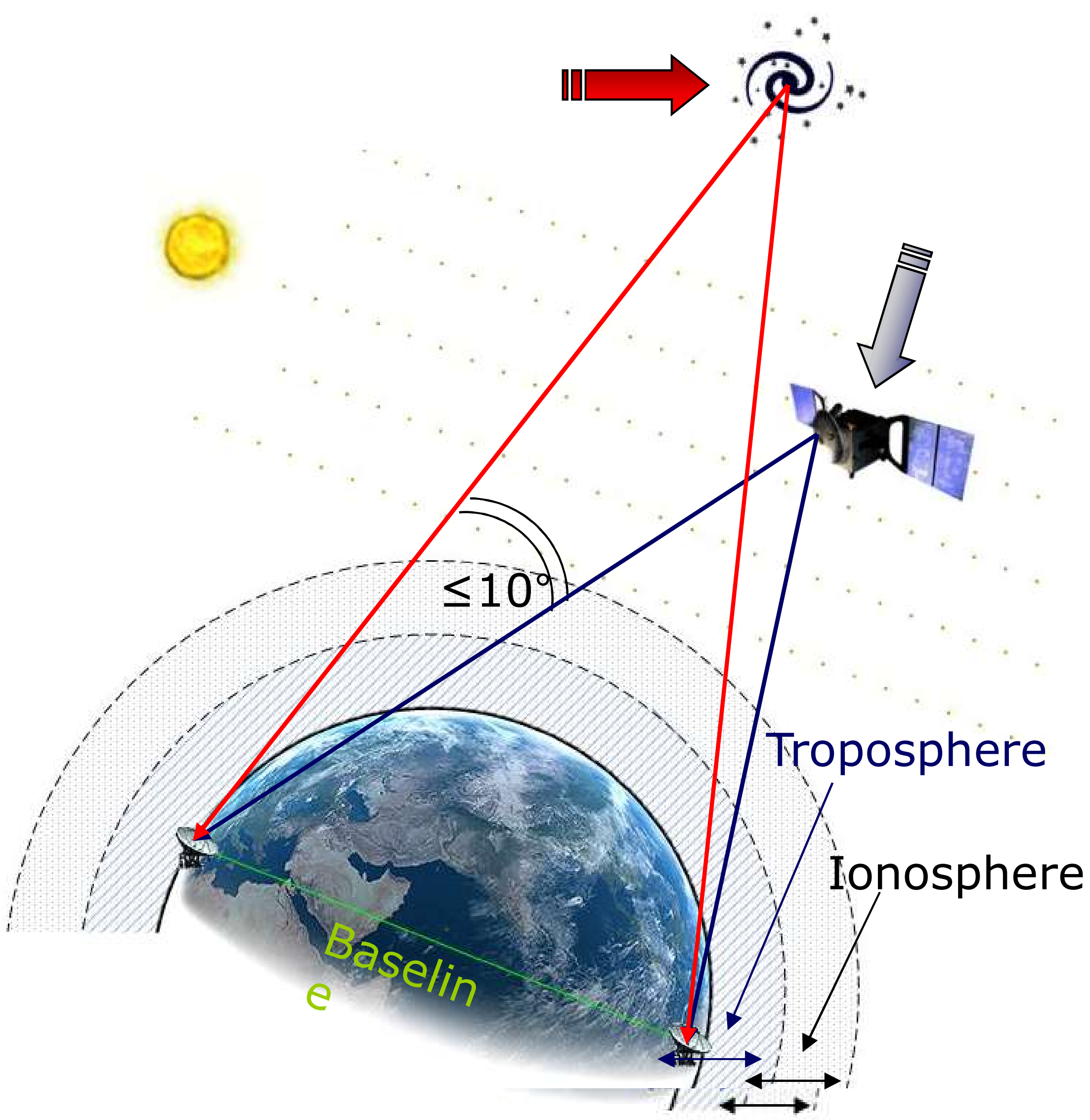
This was tested on the satellite on the launch pad. The fault was confirmed by radiating from Kourou Diane. It required shutting down the French air defence radar for South America!

The solution was to reuse some old modems from ESOC (that could sweep smoothly) and the S band up converters. These were urgently shipped out to the external stations thereby replacing their uplink chain for this LEOP.

The ground station test facility staff at ESOC developed a sweep control application in the space of an hour or so in National Instruments Labview so the sweep could be set manually and started with the click of a mouse from a laptop.

Courtesy of Kevin Kewin, ESA/ESOC

Delta-Differential One Way Ranging (D-DOR)



D-DOR is the best way we know yet to solve the plane of sky problem for deep space missions.

It measures the difference in signal arrival time between two stations.

The observable is an uncalibrated delay between the two antennas

"Delta" is respect to a simple DOR, and refers to calibration of the spacecraft DOR using the signal from a quasar!

Since the quasar signal (white noise) is recorded on the same bandwidth as the spacecraft channels then ideally any errors which are station or path dependent will cancel out!

The main error is actually the difference in clock between the two stations that has to be accurate to the nanosecond level.

Courtesy of Trevor Morley, Mattia Mercolino, ESA/ESOC

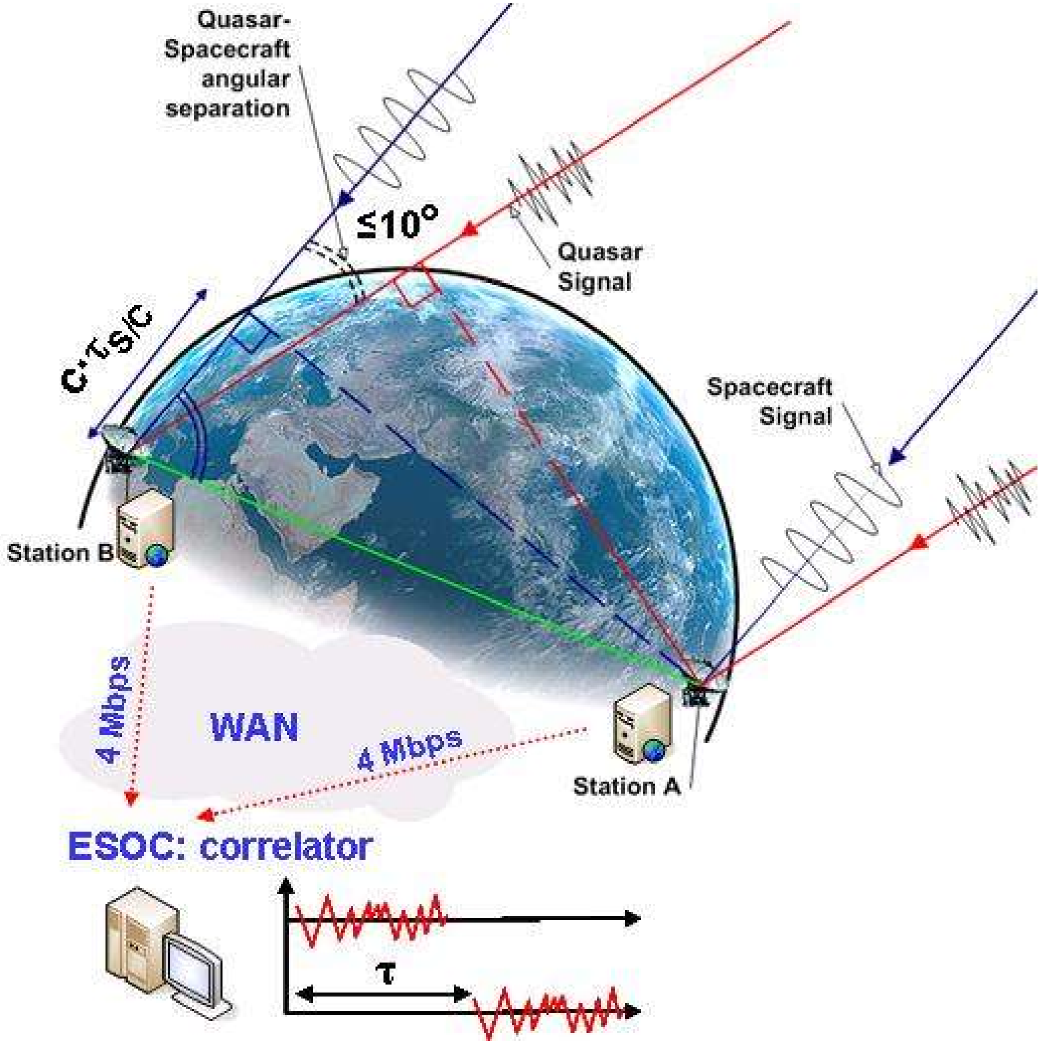
Delta-Differential One Way Ranging (D-DOR)

The extent to which these error sources cancel depends on the angular separation of the two sources being observed. The maximum angular distance between S/C and Quasar should not exceed 10 deg.

Thus, one is able to evaluate a potentially error-free relative station delay, which leads to an accurate determination of the S/C position in the plane of the sky

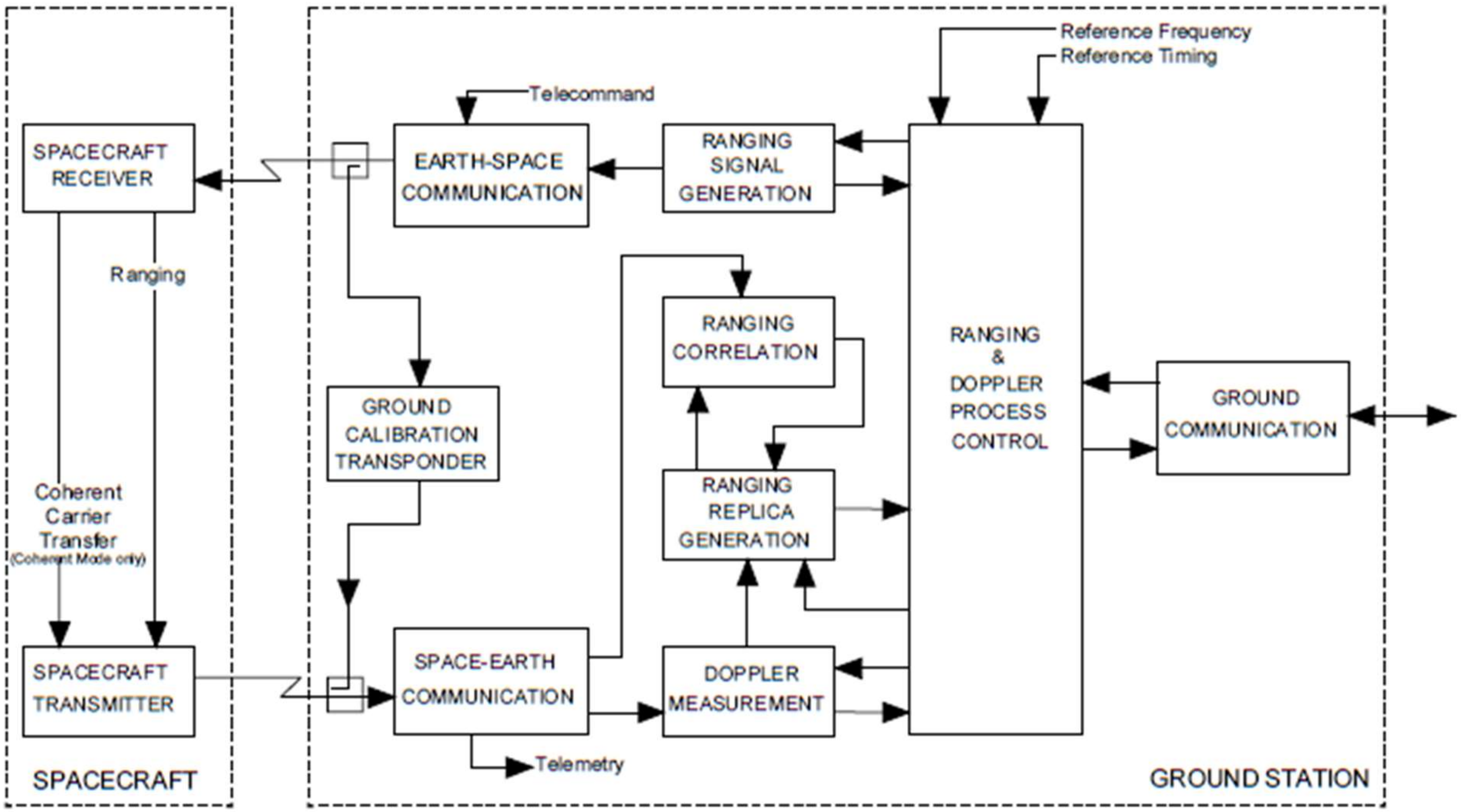
ESOC correlator requires enormous amounts of data to work (tens of GB).

The longer the baseline between the stations the higher the accuracy.



Courtesy of Trevor Morley, Mattia Mercolino, ESA/ESOC

Ranging and Doppler Summary



Have we missed anything?