SATELLITE ENGINEERING
PAYLOAD & PLATFORM

Antijamming

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Agenda – session 1

- Interferences – market analysis
- Bent pipes architectures (TV broadcast)
  - Shaped antenna
  - Ground geolocation
- Multibeam architecture (Internet)
  - Flexible input section
  - Processors
  - Carrier ID

Agenda – session 2

- Advanced Geolocation
  - MUSIC and CAPON
- Active antenna architecture
  - Analogue and Digital solutions
  - Geographic nulling
- Frequency hopping

Introduction

- Antijamming is a must have in military satellite
- But interferences are more and more frequent in commercial satellite
  - Commercial customer ask for anti interferences solutions

- This session will start from basic architecture to complex one and explain what can be done to fight against interferences
- Not an exhaustive view of all antijamming solutions : there are too many !

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Antijamming – Market analysis

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Type of interferences

Unwanted emissions

may interfere with passive sensors (like SMOS)

In-band emissions

Interference internal to the satellite system (malfunction, improper settings), This is outside of the scope of the Radio Regulations Authorities and is dealt with internally by satellite operators.

Interference external to the satellite system

Adjacent satellite interference: either errors (e.g. antenna miss-pointing) or lack of coordination

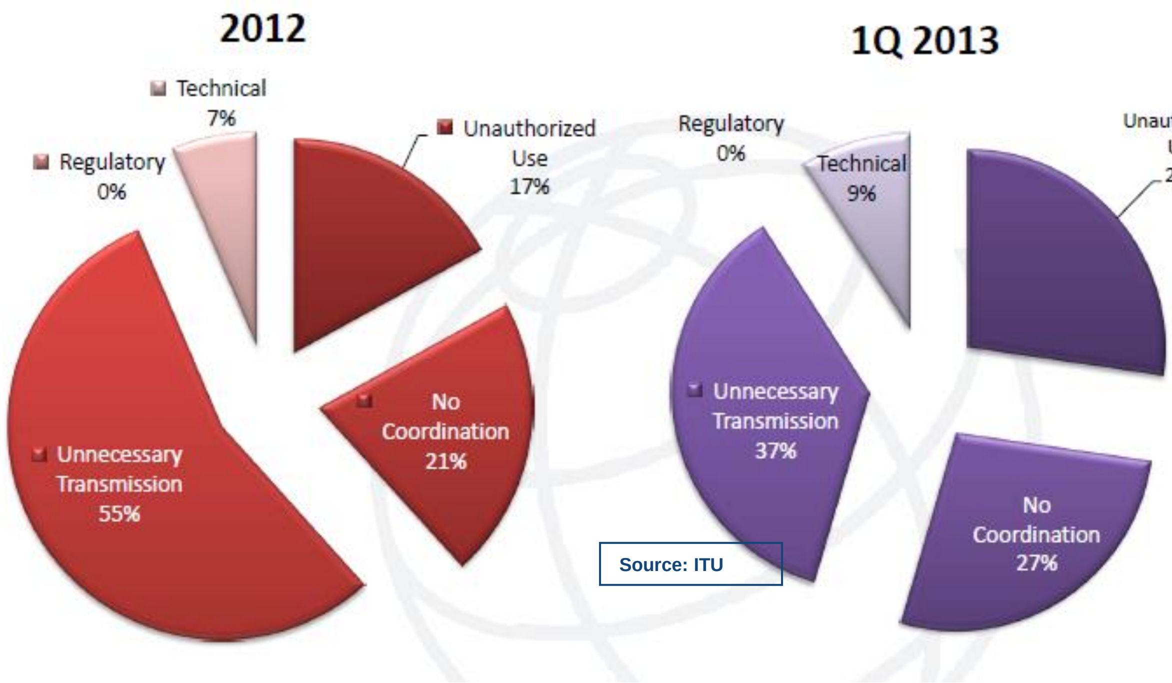
Unauthorized access to the satellite:

Carriers (with content) are transmitted towards a satellite without any prior contract/authorisation is put in place with the satellite operator (e.g. piracy)

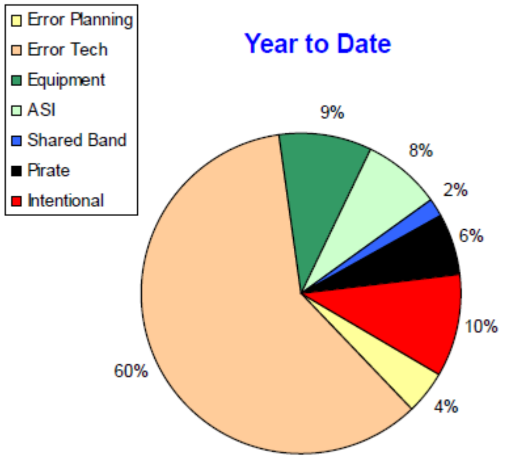
Intentional jamming of satellite signals:

Carriers (often unmodulated) are transmitted towards a satellite with the intent to prevent the current signals to be transmitted.

Types of interferences - Statistics



Source: ITU



Source: Eutelsat - 2012

Increase of interferences – Non intentional and intentional

Effects of jamming

- Jamming is a deliberate interference, by definition directed at specific targets: mainly international news channels such as BBC channels, Voice of America, Deutsche Welle, France 24 and others like Al Jazeera or CCTV (China).

- Practically, for the citizens of the world, deliberate jamming means a blank screen and the fact that the information they are looking for does not reach them.

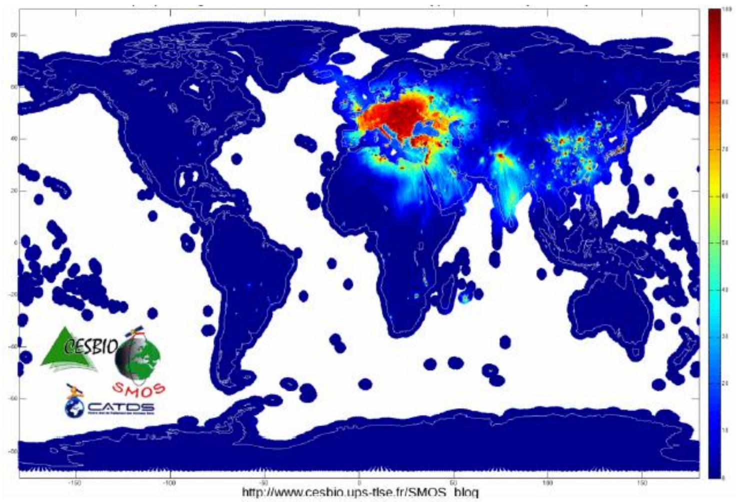
- However, as we are living in a 100% digital environment, it is not just reception of the targeted channel that is damaged, but all the channels in a multiplex.

- Up to ten to twelve channels can be affected when one channel is targeted, representing huge collateral damage. This situation becomes even more acute when there is random jamming that sweeps from one transponder to the other with the purpose of inflicting as much harm as possible.

- Eutelsat have been using geolocation techniques in collaboration with the European Broadcasting Union which has enabled unambiguous identification of the origin of jamming in 30% of cases since 2010. Of this 30%, 40% came from Iran and 50% from Syria.

Intentional Interference – Commercial Satellites

- Less than 10% of all interference world wide is considered to be “intentional“
- Most occurrences are reported in the Middle East and Africa
- Broadcast satellites are most commonly targeted with certain channels being the most highly affected, a report from Eutelsat in 2013 identified the channels suffering the most interference are those of international news channels (such as BBC, Voice of America, Deutsche Welle, Al Jazeera etc.)



Probability of sustained hard RFO occurrences (no outliers detection) for 20120912 ± 07 days perios from BB post-processing of OPER/REPR SML2 UDP & DAP – ASCENDING only passes – Dual & Full polarizations products

Reaction the jamming

- A full anti-interference process follows usually these **3 steps**

Detection
- We need to know first that a jamming is occurring
- It can be done by power detection, BER alert…

Geolocation
- The source of interference has to be located
- Geolocation is not necessary in specific system like frequency hopping

Recovery
- If it’s a source from the system : we can stop it
- If it’s an exterior source, we have to reduce its impact on the useful signal

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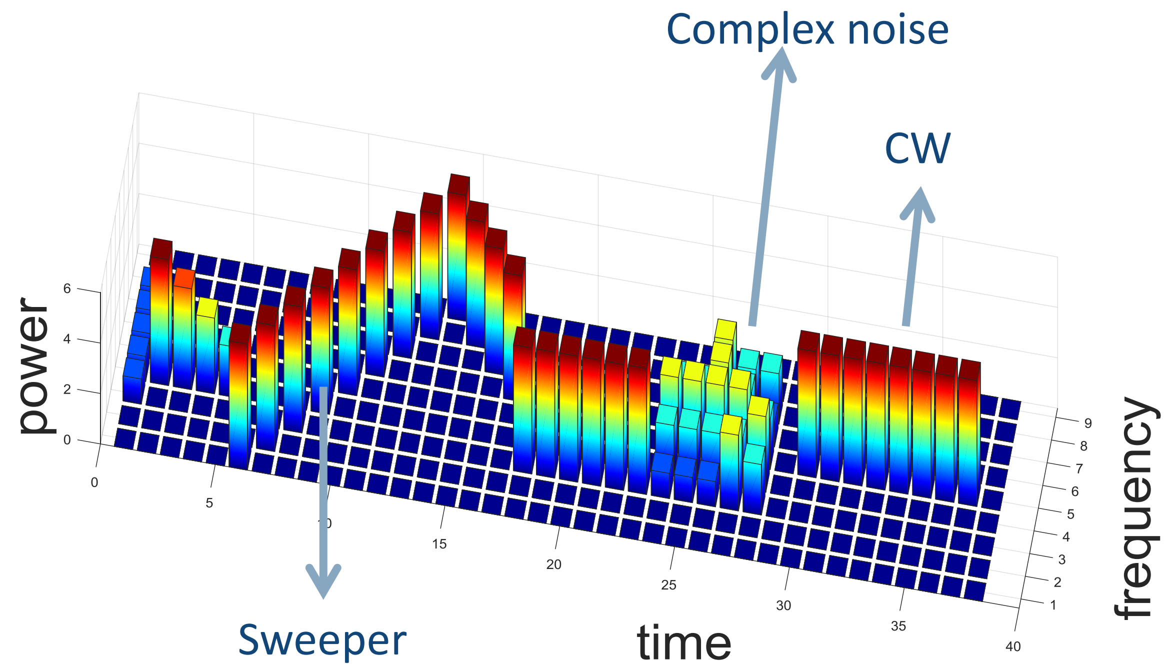
Jamming signal properties

- The jammer signal can vary in term of :
  - Power
  - Frequency
  - Time



Mathematical functions required – Cross correlation

- Used to measure delay between two signals
- Very useful for ground geoloc solutions

$$\Gamma_{AB}(\tau) = \int A(t)B^*(t-\tau)$$

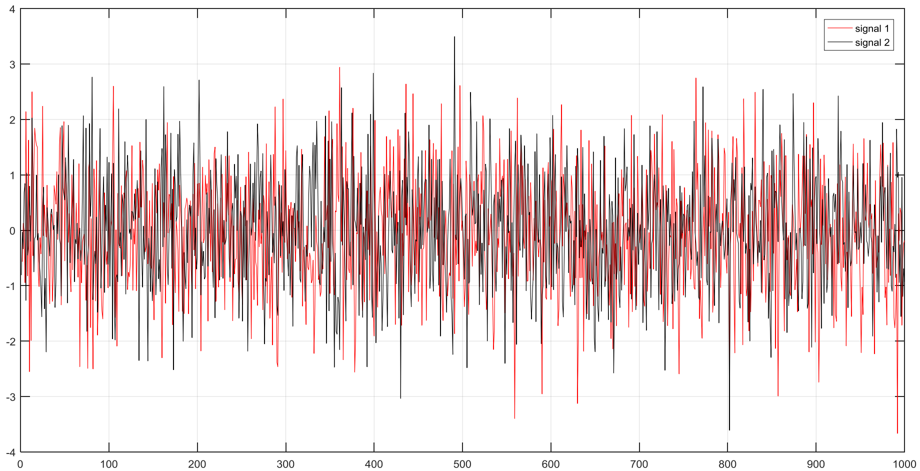
Cross Correlation of two signals A and B

If A and B are totally uncorrelated, $\Gamma_{AB} = 0$

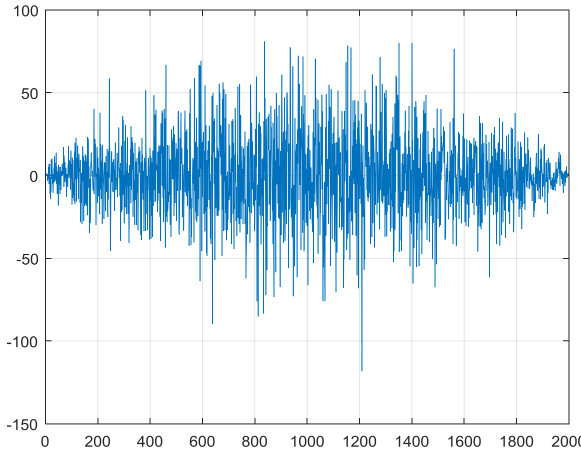
- The correlation between two independant noises is equal to 0

If A and B are correlated and delayed by τ_{delay}, the function Γ is maximal when $\tau = \tau_{delay}$

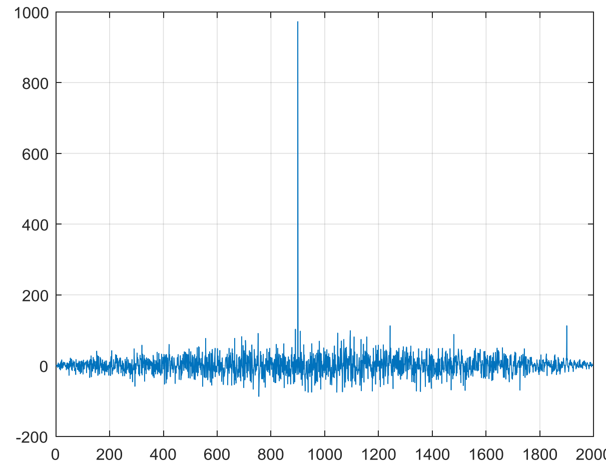
Examples : Noisy signals



Signals 1 and 2 are un correlated

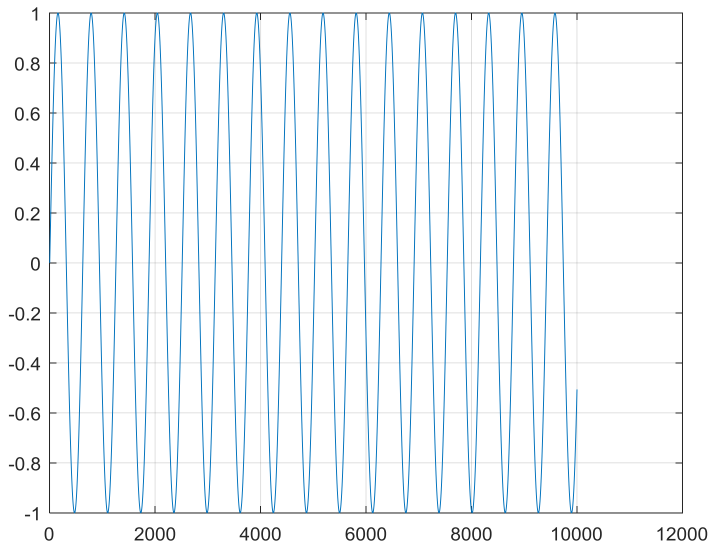


Cross correlation of signal 1 and signal 2

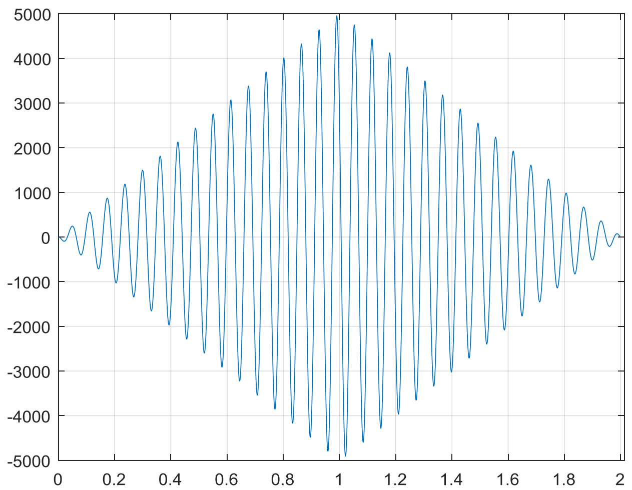


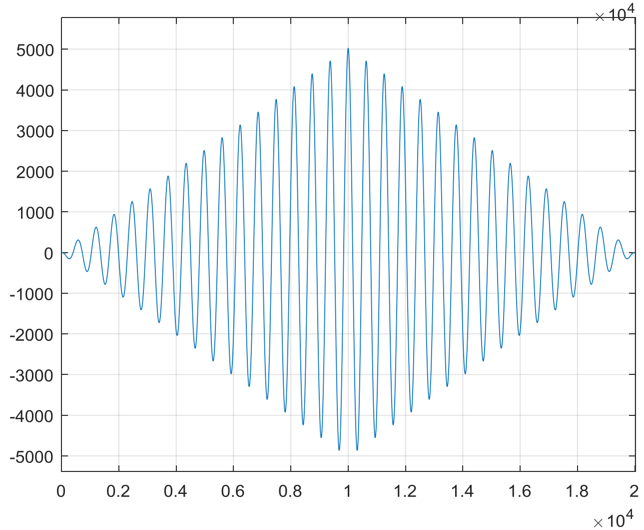
Cross correlation of signal 1 and signal 1 delayed by 100 samples

Examples : CW signals



CW signal





Cross correlated with itself delayed and not delayed…

Mathematical functions required – Covariance

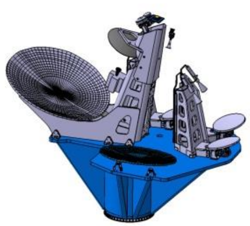
- Used to measure phase variations
- Very useful for on board solution with processor
- Used for high resolution technic of geolocation
- And for antijamming with processor
- The function is implemented like this :

$$Cov_{estimated}(A,B) = \frac{1}{N_{samples}} \sum_{t=0}^{N_{samples}} A(t)B^*(t) - \cancel{\bar{A}\bar{B}}$$

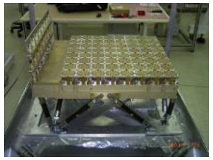
=0 for telecom signals

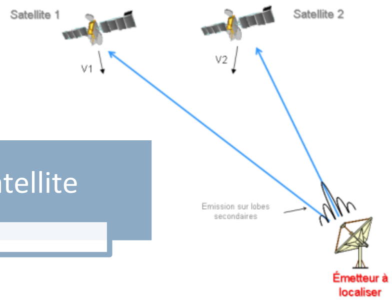
$$Cov_{estimated}(A,B) = \frac{1}{N_{samples}} \sum_{t=0}^{N_{samples}} A(t)B^*(t)$$

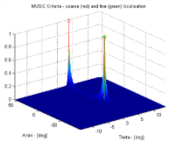
GEOLOCATION – Main class of methods



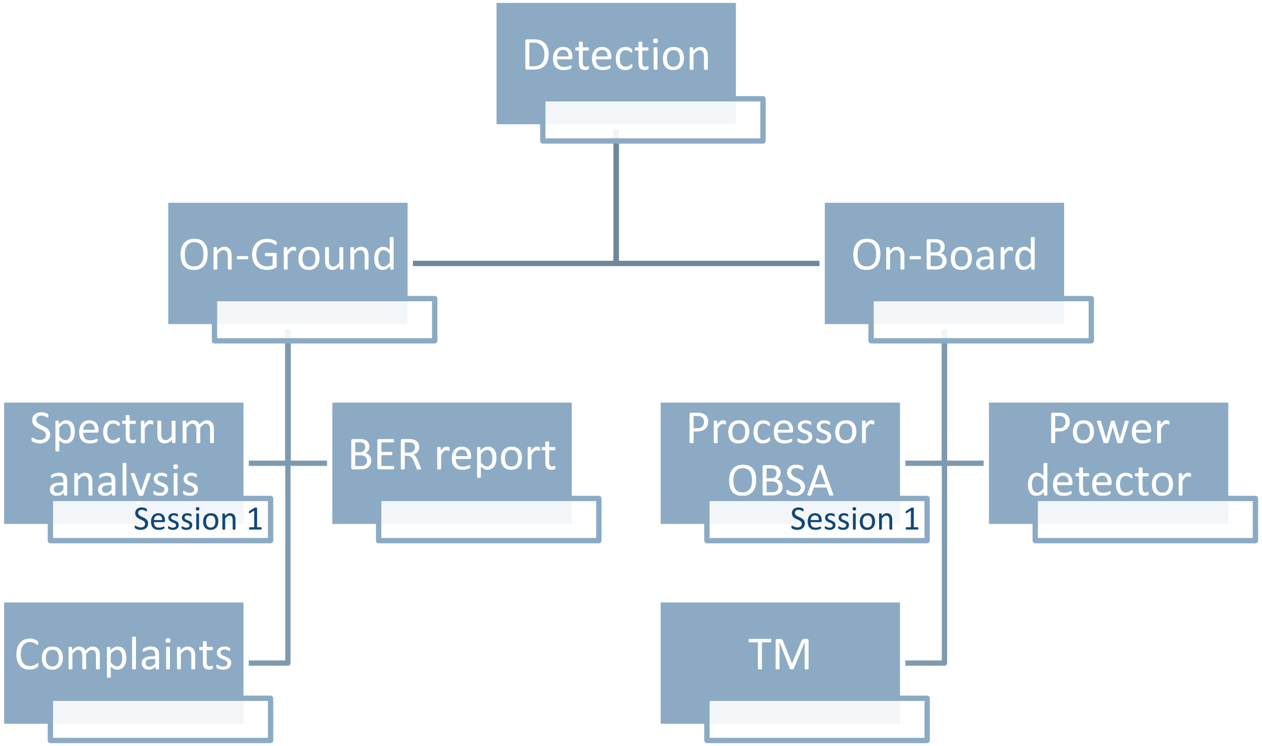
- Geolocation
  - Mono Satellite
    - Steerable antennas
      - Conical Scan — Session 1
      - Monopulse Ecartometer — N/A
    - Active antenna — Session 2
      - Conical Scan — Session 2
      - High Resolution — Session 2
  - Multi Satellite
    - Mirroring — Session 1



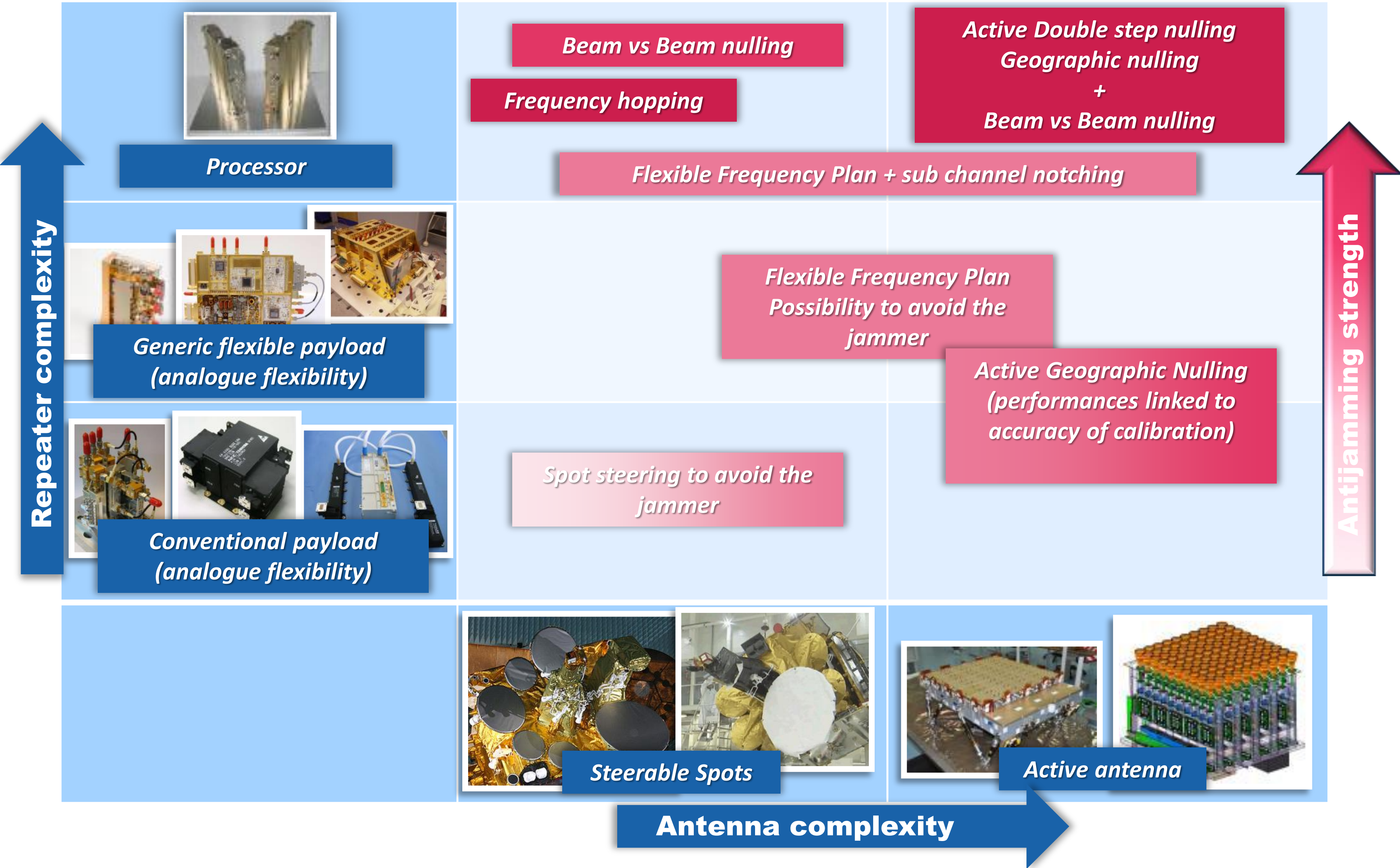




DETECTION – Main class of method



Antijamming : Summary of on-board solutions



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Bent pipes architectures

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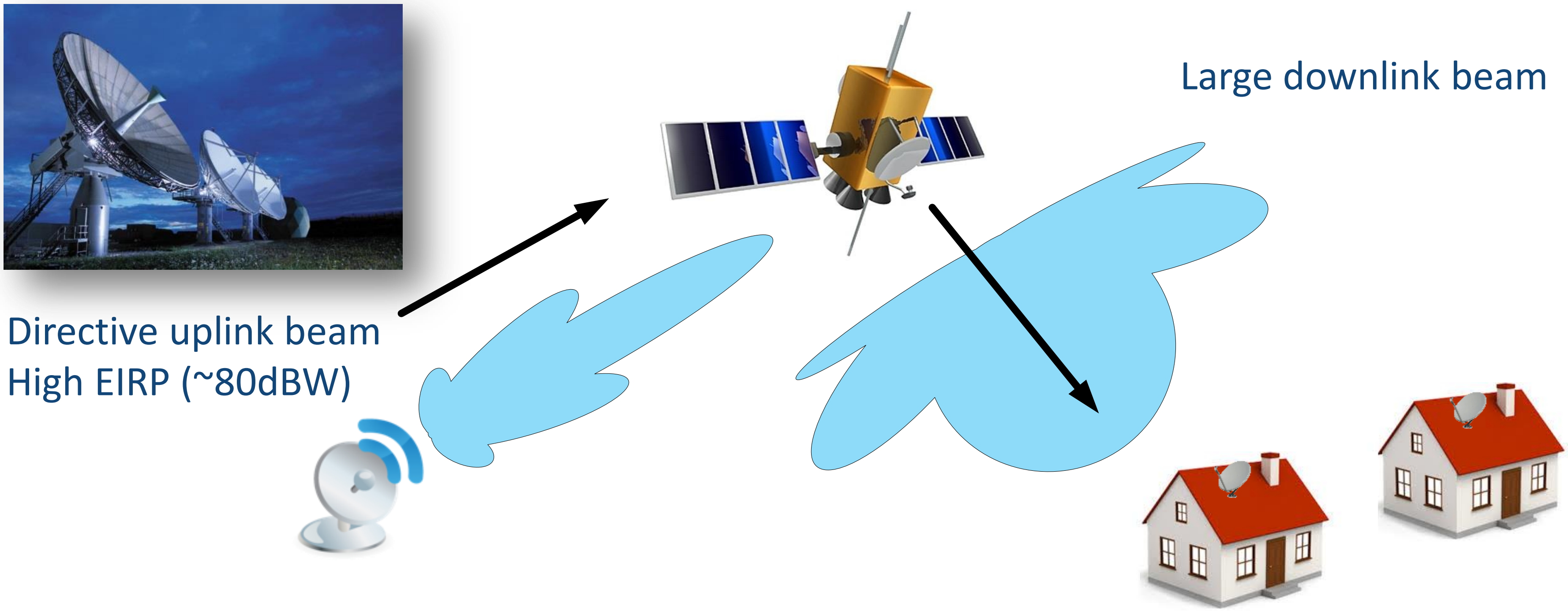
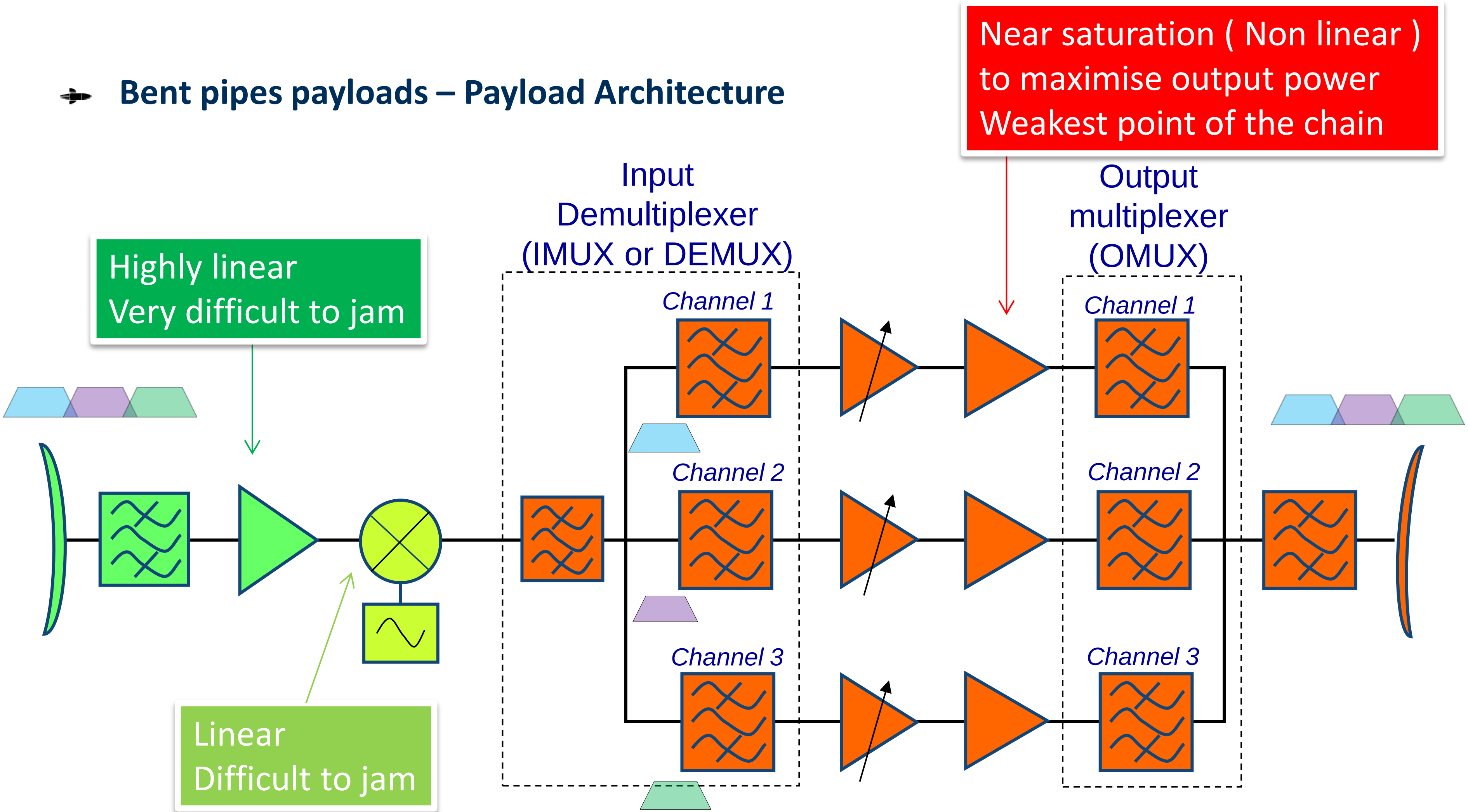
Bent pipes payloads – System Architecture

One Gateway send the TV channels to the satellite
Then the satellite broadcast the channels over a large area (Continent)



One way system : Gateway to Users

Bent pipes payloads – Payload Architecture

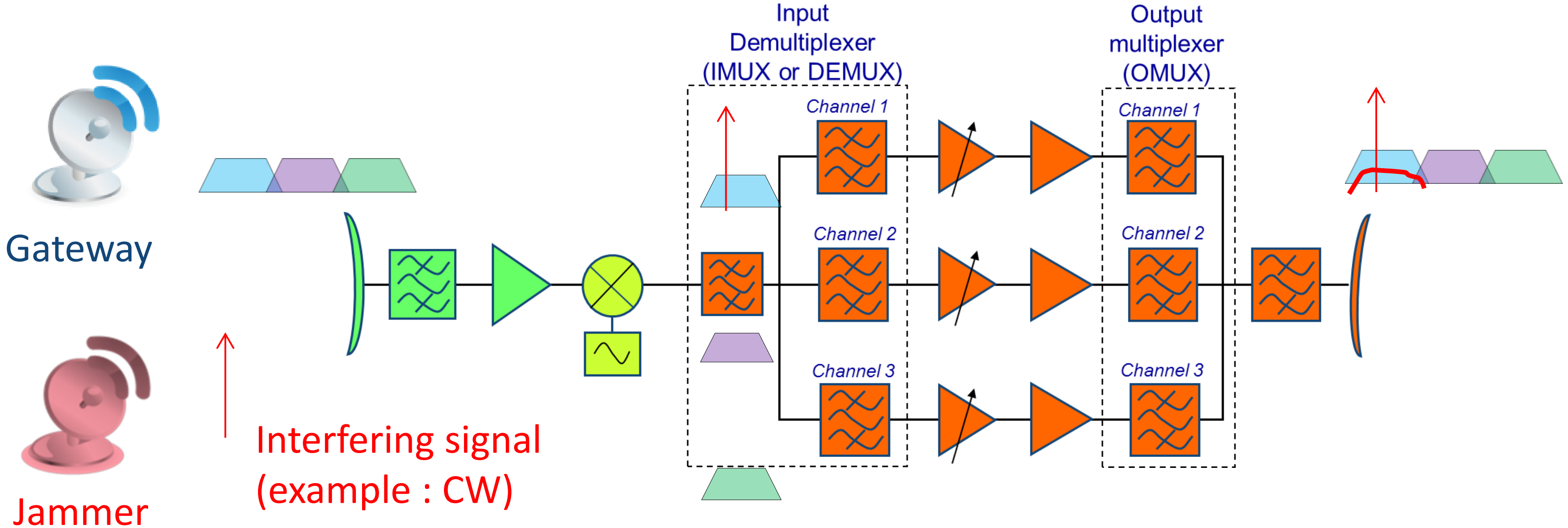


Start of one RF path will better resist to interferences than the end

Bent pipes payloads – Typical jamming

High EIRP required for the jammer to jam the uplink

Typical Gateway EIRP is around 80dBW for 40 TV channels i.e. around 64dBW per channel



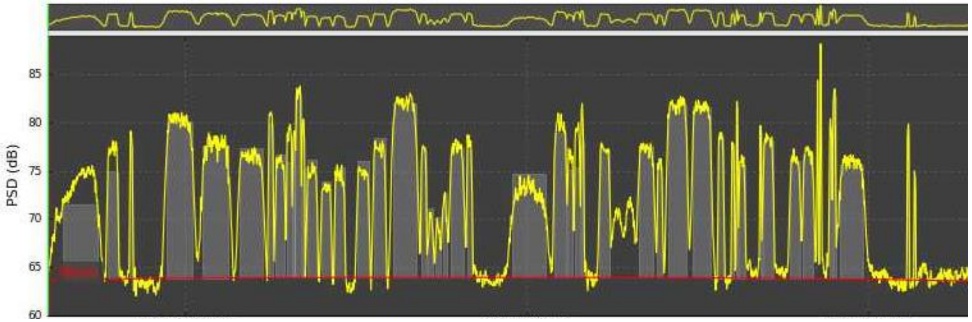
TV satellite interferences are intentional due to the high EIRP required

Some ground EIRP order of magnitude

	Ku user	Ka user	Ka mil user	Ka mobile teleport	Ka GW	Ka GW	Ka GW	
Power	10	10	10	100	500	500	500	W
Diameter	0.4	0.4	0.45	1	1.2	3.6	4.8	m
f	14	30	31	30	30	30	30	GHz
lambda	0.02	0.01	0.01	0.01	0.01	0.01	0.01	m
theta 3dB	3.75	1.75	1.50	0.70	0.58	0.19	0.15	degrees
Gmax	33.13	39.75	41.05	47.70	49.29	58.83	61.33	dB
EIRP	41.1	47.7	49.1	65.7	74.3	83.8	86.3	dBW

Detection

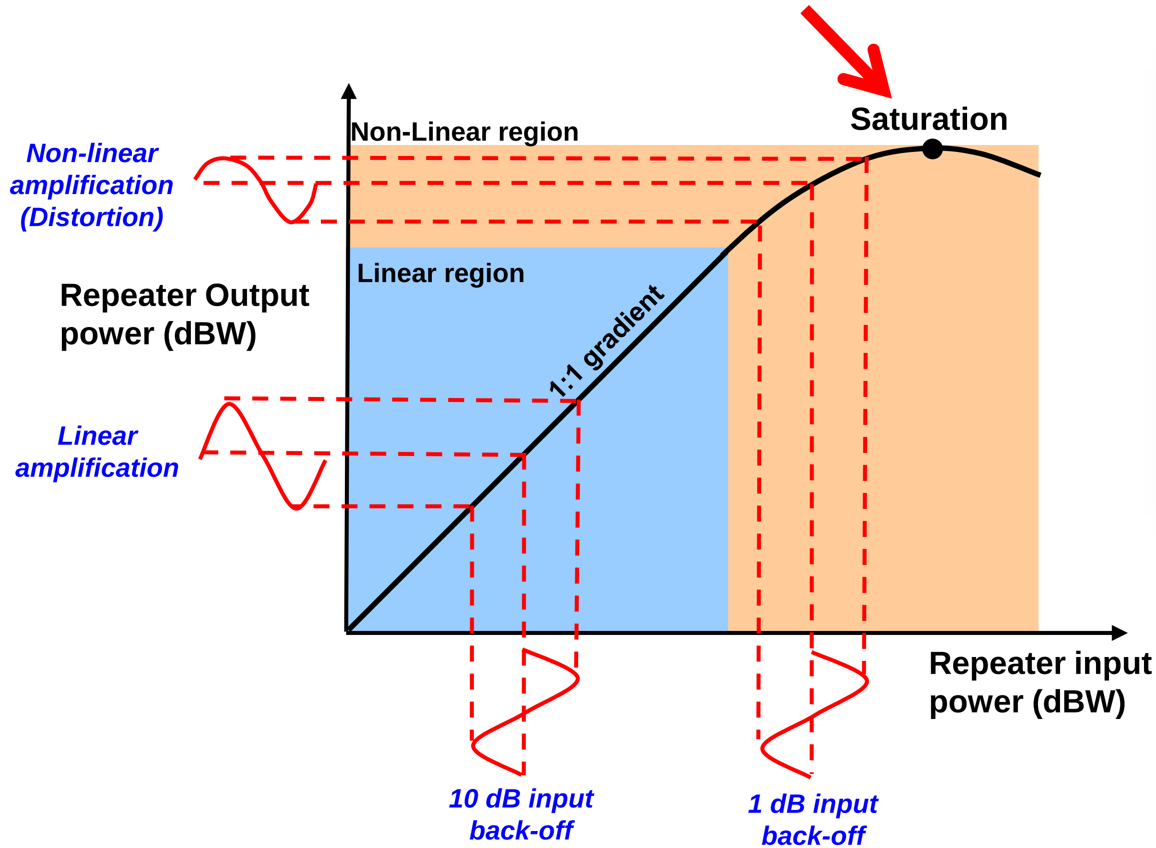
- Detection on a bent pipe architecture is quite simple as the gateway is often in the Tx coverage
- On ground measurement :
  - Spectrum analyser
    - With threshold on the power spectral density
  - Demodulating the signals
    - Decoding and calculation of BER

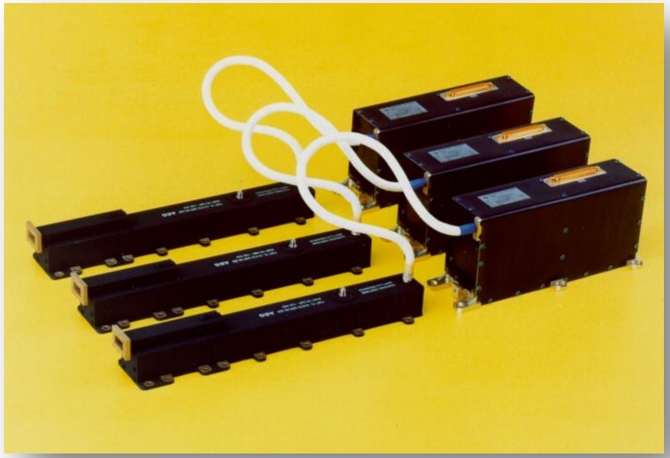


Power robbing

- A classical threat is to send a high power signal into the satellite to robb the power of the high power amplifier (HPA) by driving it near saturation

The jammer will try to drive this area



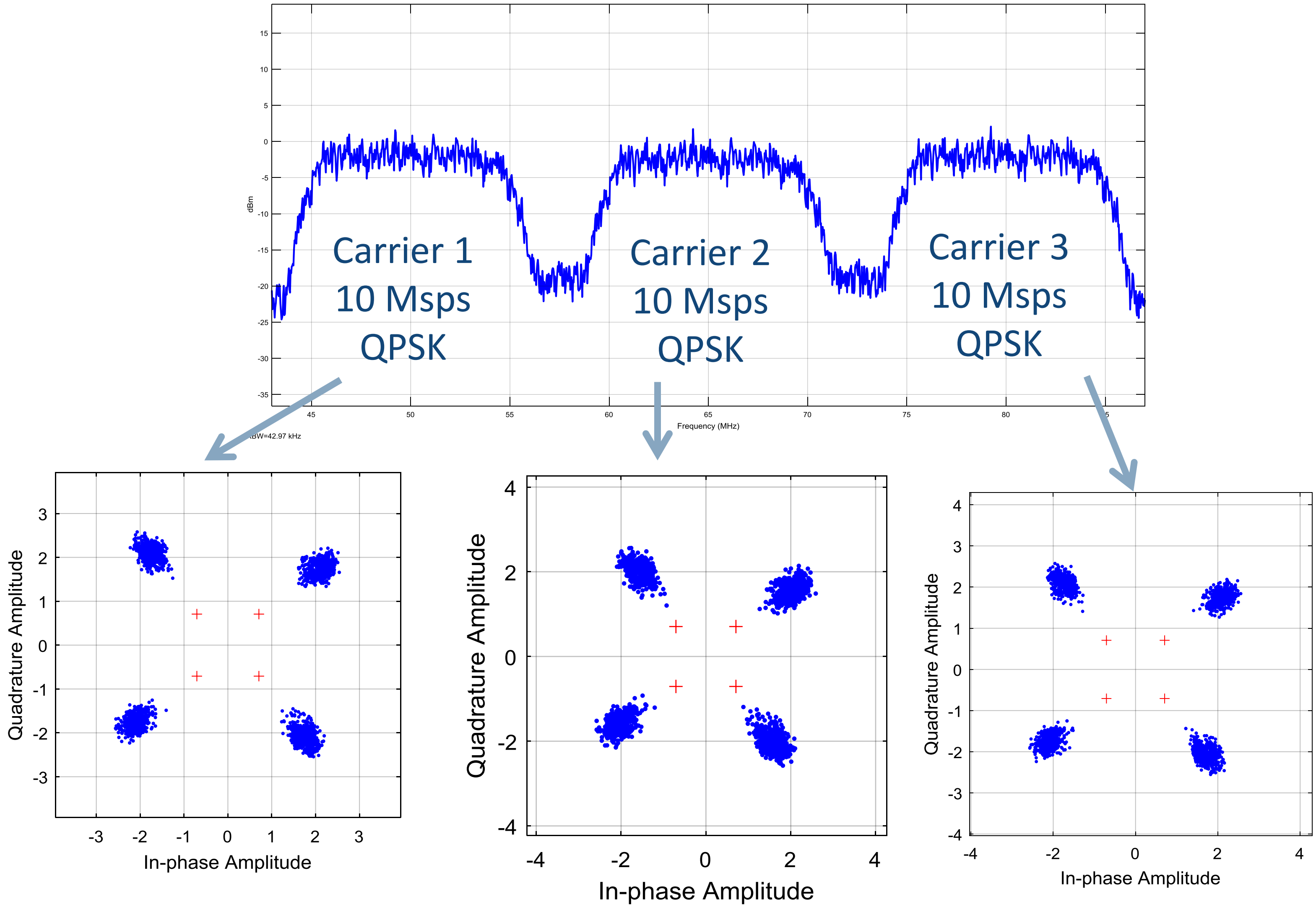


TWTA
Travelling Wave Tube Amplifier

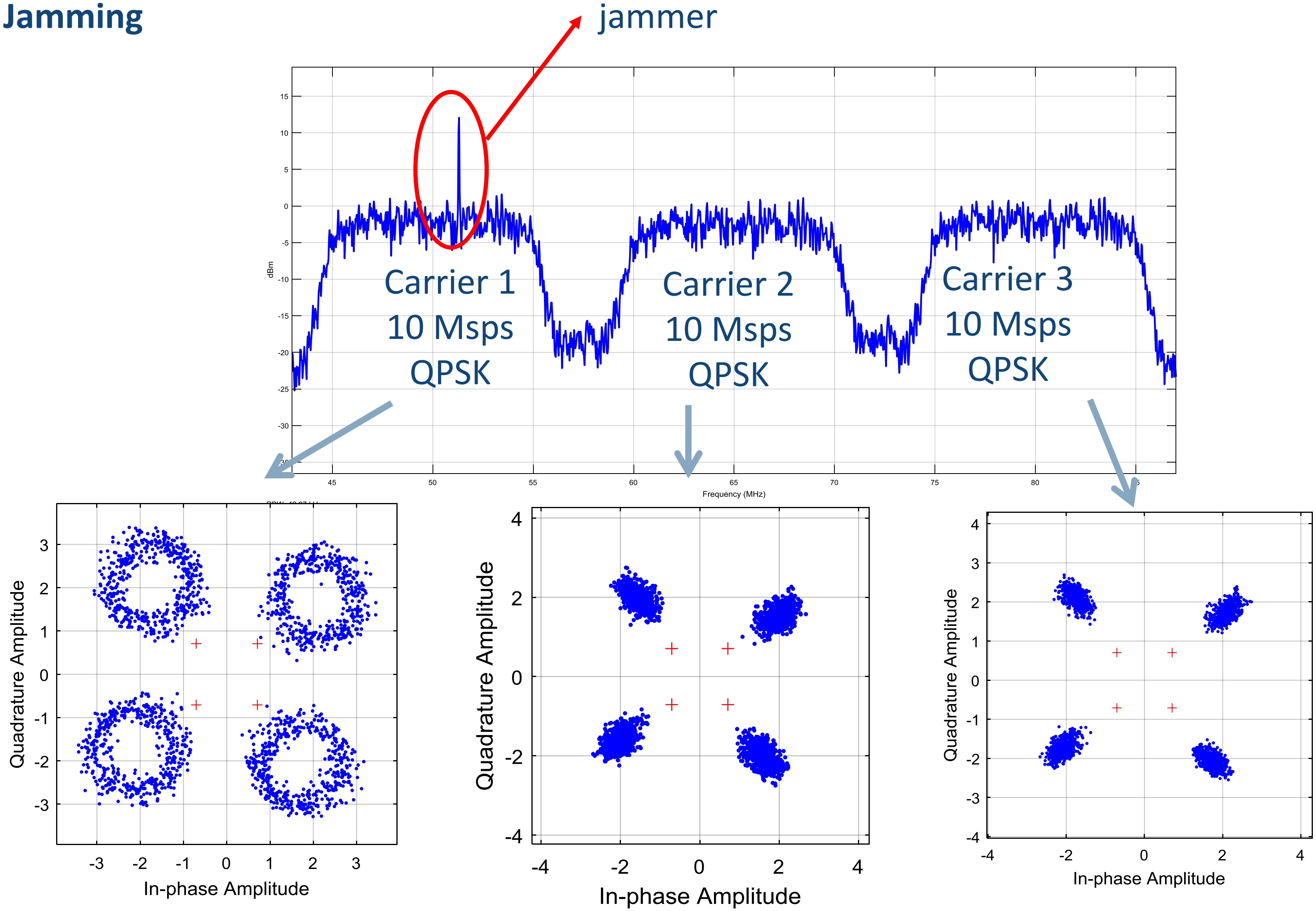
Power Robbing example

- On the next slides, we will see an example of bent pipe carrier used to transmit 3 TV channels
- A CW jammer will be used to jam the first channel
- By increasing the jammer pwoer level, we will see how the other channels are impacted

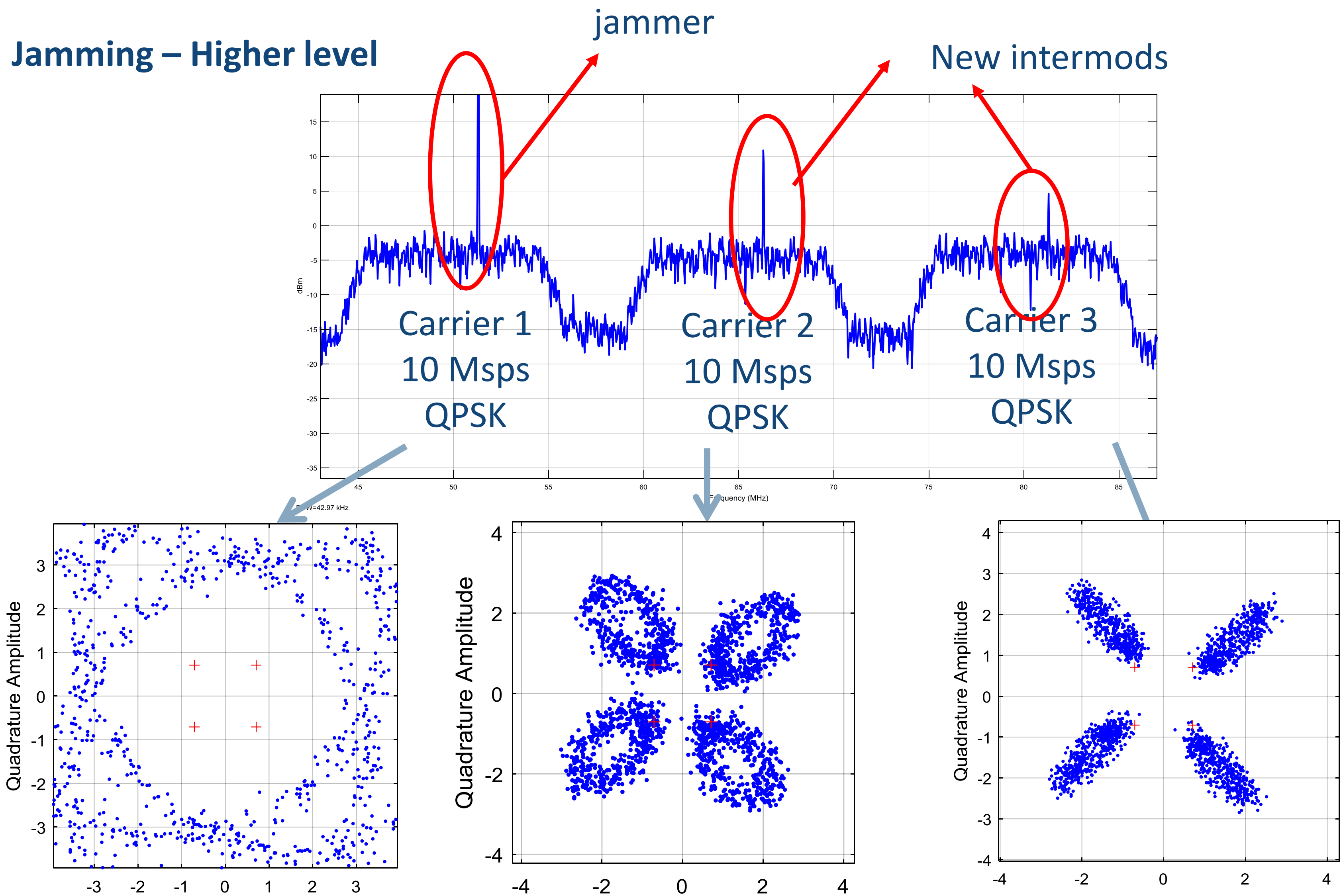
No jamming


Carrier 1
10 Msps
QPSK
Carrier 2
10 Msps
QPSK
Carrier 3
10 Msps
QPSK
dBm
Frequency (MHz)
In-phase Amplitude
Quadrature Amplitude

Jamming


jammer
Carrier 1
10 Msps
QPSK
Carrier 2
10 Msps
QPSK
Carrier 3
10 Msps
QPSK
dBm
Frequency (MHz)
Quadrature Amplitude
In-phase Amplitude
Quadrature Amplitude
In-phase Amplitude
Quadrature Amplitude
In-phase Amplitude

Jamming – Higher level



Even a simple CW jammer can affect several channels by saturating the chain

Power Robbing – Conclusion

- The power robbing in the TWT is often the purpose of an intentionnal jammer
- The waveform can remain quite simple (CW). It's mainly a question of EIRP
- Being able to saturate the transponder, even from a narrow band, will impact the full channel
- Advanced payload architectures will help to **intercept the interferer before the TWT to avoid power robbing and signals distorsion**

Protecting the output section is a basis of antijamming architectures

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On ground geolocation system

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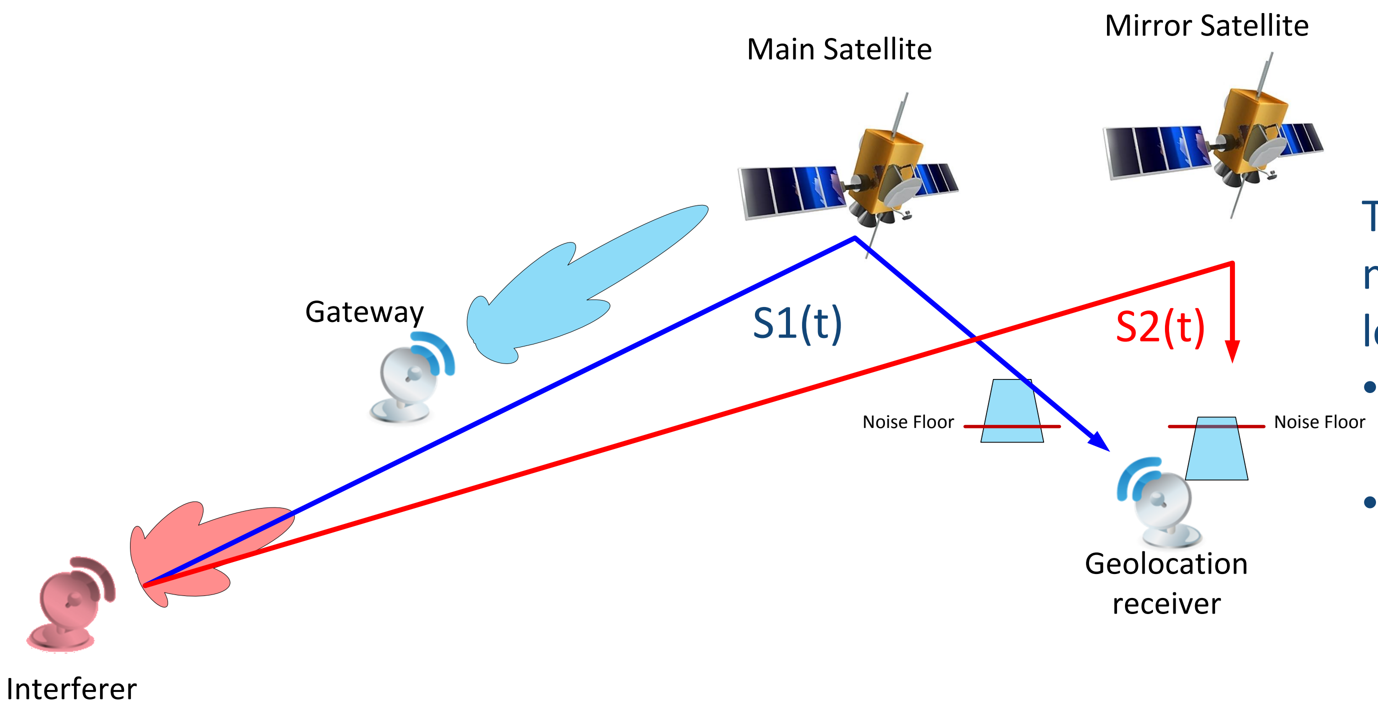
On-ground Geolocation system

- Classical bent pipes payload are not designed to react to interferences
- The reaction has to be done on ground
- The classical on-ground method is based on mirroring with FDOA / TDOA technic
    - Another satellite with a similar transponder is used to transmit a copy of the interference
    - This copy will follow another RF path providing different propagation time and different doppler effect
    - These two informations will provide an approximation of the source coordinates

Geolocation by mirror satellite – FDOA / TDOA



The signal from the mirror satellite has a lower power :

- Secondary lobe from the emitting antenna
- And from the receiving antenna of the mirror satellite

TDOA

- The ground system does a cross correlation between s1 and s2 where :

$$s_1(t) = s_{useful}(t) + A \times s_{jammer}(t) + N_1(t)$$

$$s_2(t) = \varepsilon \times s_{useful}(t + \Delta t1) + B \times s_{jammer}(t + \Delta t2) + N_2(t)$$

- The peak of cross correlation between s1 and s2 provides the delay between the two signals

$$\Gamma_{s1\ s2} \approx \Gamma_{sjammer(t)\ \ sjammer(t+\Delta t2)}$$

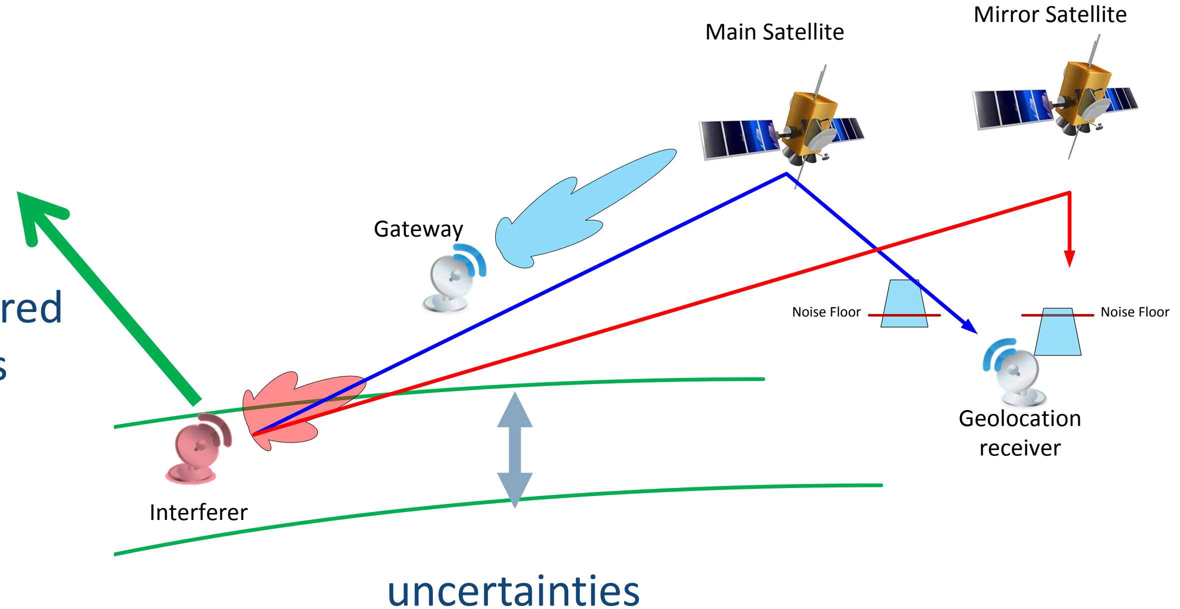
  - As all signals are supposed to be uncorrelated

TDOA

Area where should be the interferer

The uncertainties can be lowered by increasing the time of cross correlation

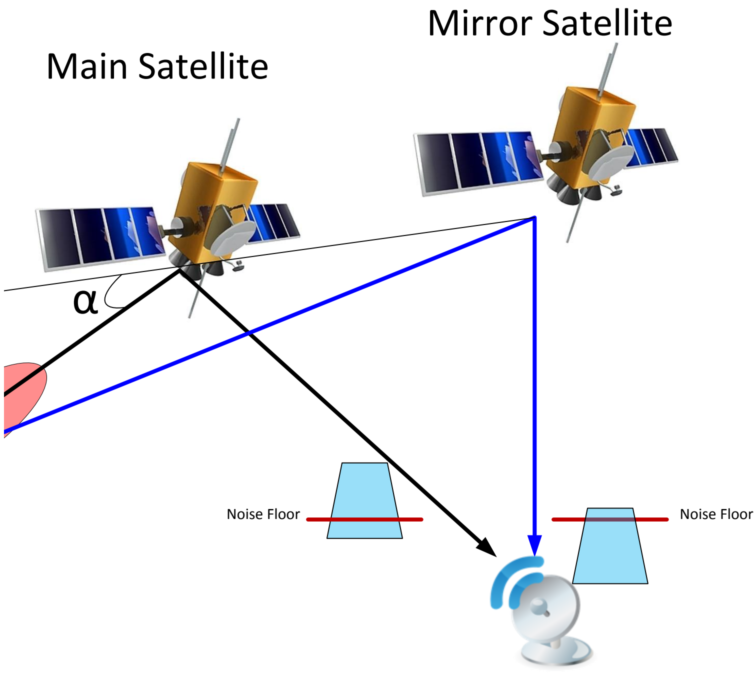
But can't be reduced to zero
- Noise in measurement
- Some useful signal remaining in the mirror path with a different delay



Typical uncertainties : hundreds of kilometers

FDOA

- The FDOA gives the other dimension
- The two satellites are moving with respect to the earth and are creating both a doppler effect on the signals
  - The doppler effects are differents as the two satellites are on two different orbital locations
  - We measure the doppler effect (Δf) from the two satellites
  - Δf1- Δf2 provides an estimation of the angle α



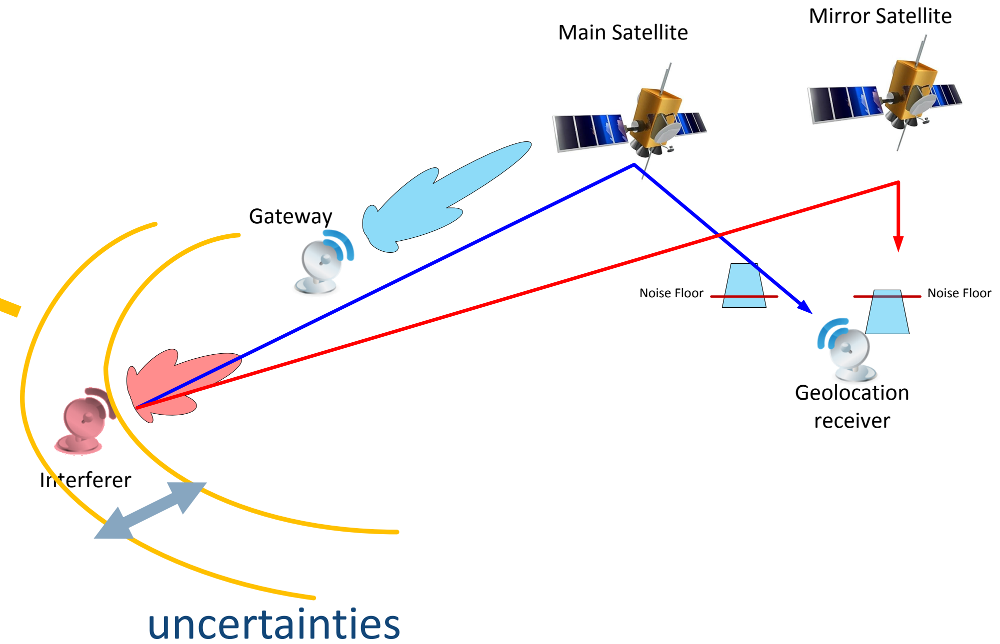
FDOA

Area where should be the interferer

The uncertainties can be lowered by increasing the time of cross correlation

FDOA measurement is sensitive to the bandwidth of the emitter

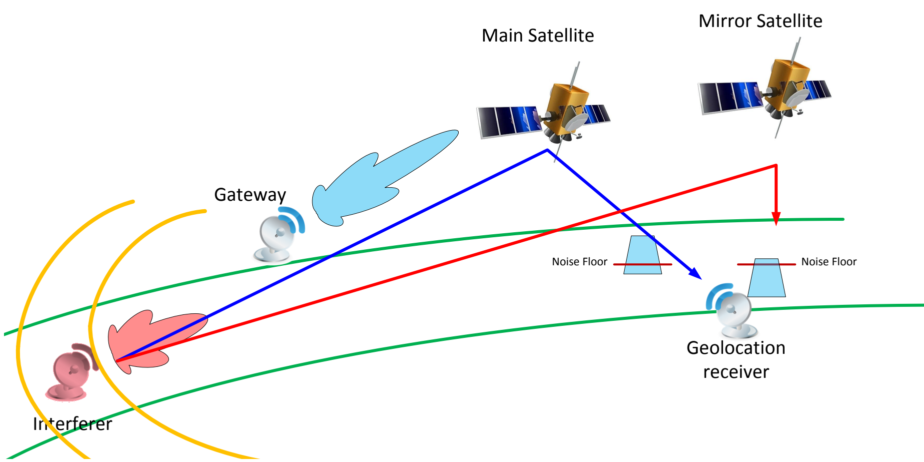
Like the TDOA, it's sensitive to the signal SNR and the time of correlation

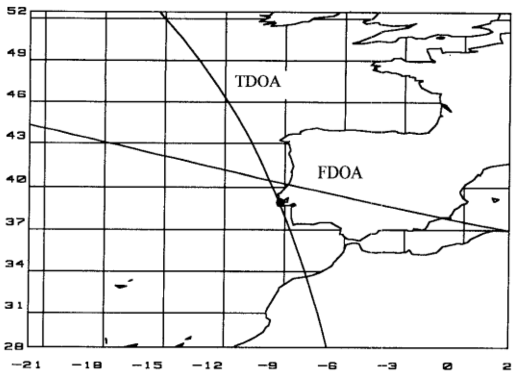


Typical uncertainties : hundreds of kilometers

TDOA / FDOA

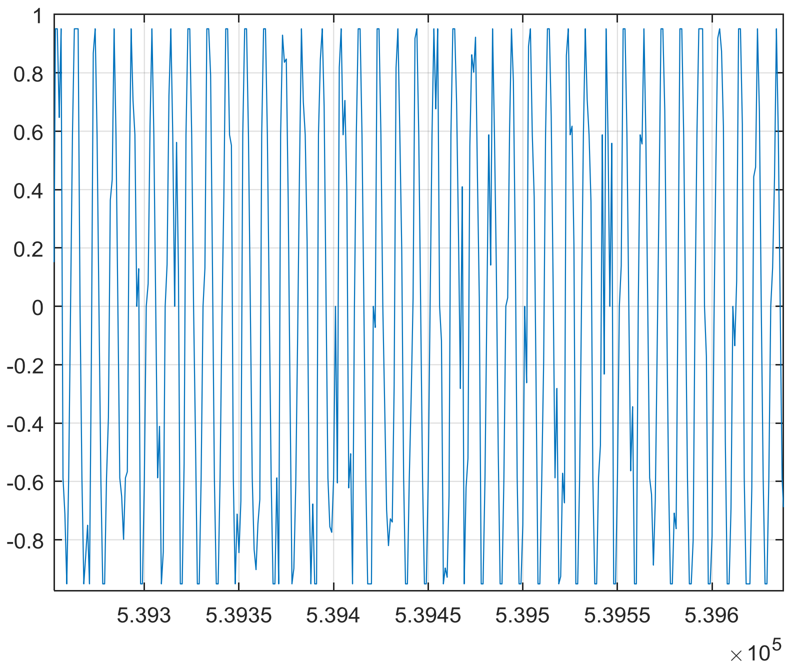
- Requires a mirror satellite
  - Ok for Ku band
  - Difficult in Ka band as few satellites are available
- Doesn't work very well with CW jammer
  - Need a very long time of correlation (several hours)
    - Using RF impairments like phase noise
- Difficult to geolocate sweepers
- Pulsed jammers with long off period are difficult to manage



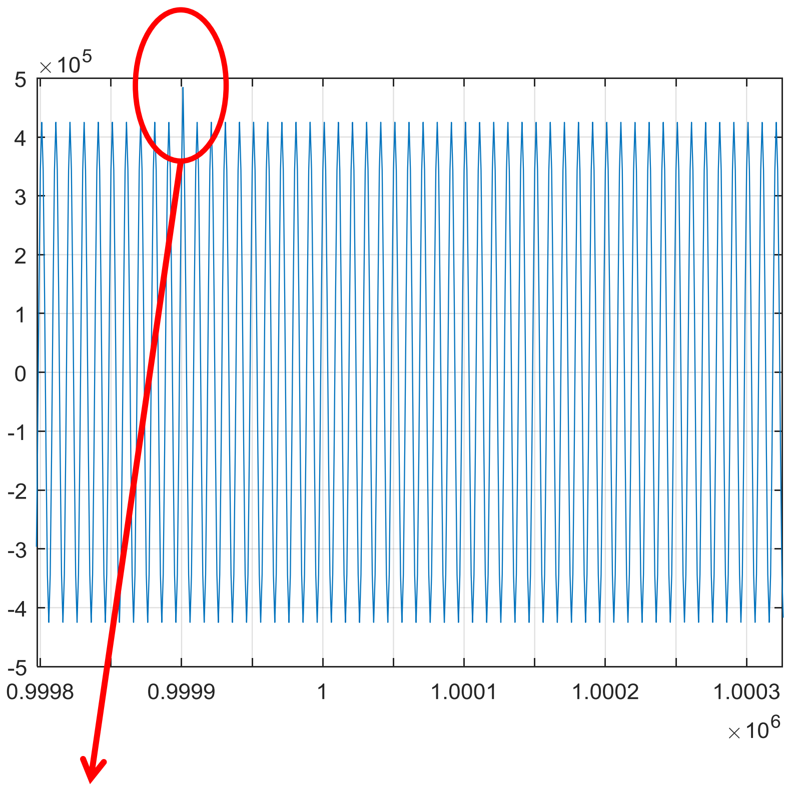


Typical TDOA /FDOA measurement
Ref : Interference Localisation for the Eutelsat satellite system

TDOA with CW



Signal with phase noise (exaggerated on the figure)



Will generate a spike indicating the delay
Known frequency can also be filter to help convergence

Ground Geolocation system : TDOA / FDOA

- Affordable solution
- No on-board impact : keep simple design
- Need a mirror satellite
  - Few chance to have one in Ka
- Simple and common waveform like CW are difficult to geolocate as the pattern is static in time
- Could requires hours of measurement to get enough data in order to correlate signals with accuracy
  - Erratic jammers can be very difficult to catch and measure

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Steerable antenna / Regulatory aspects

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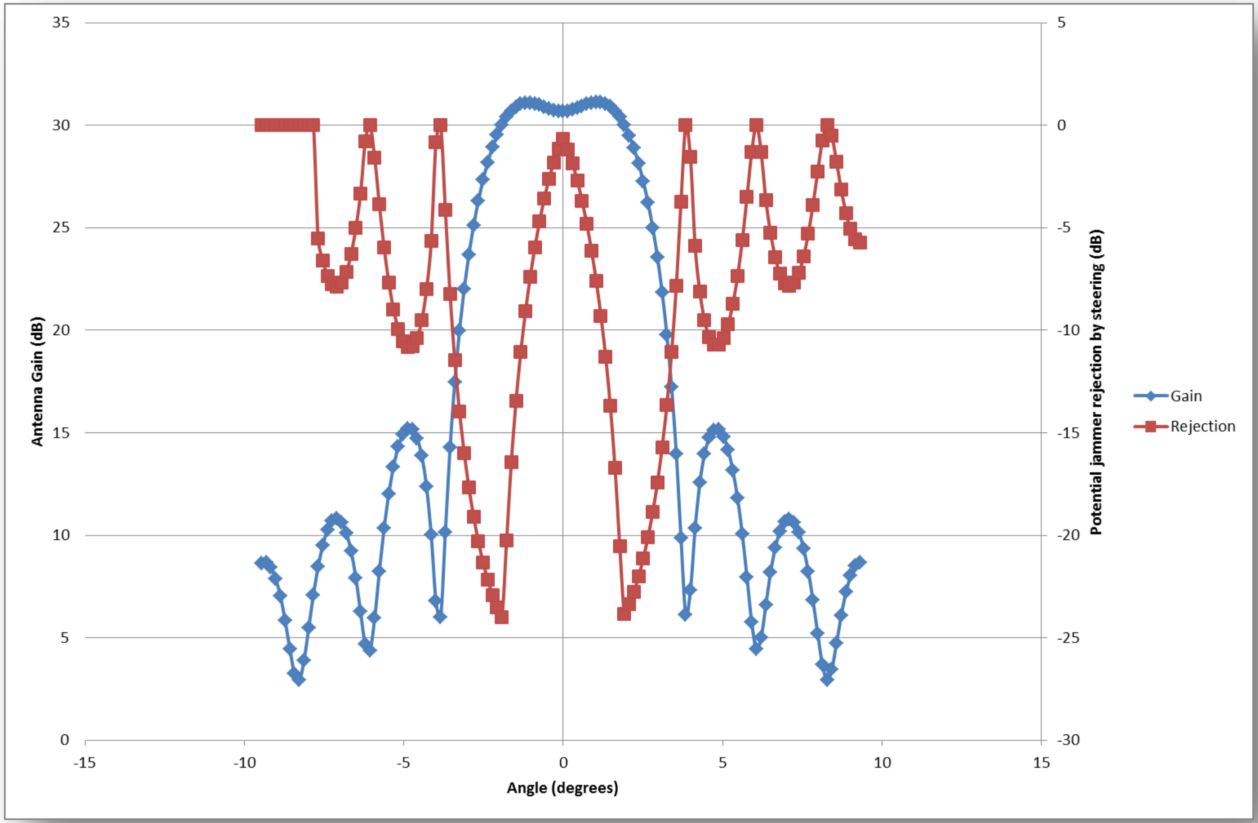
Signal recovery – Regulation aspects

- A classical bent pipe satellite have few (and sometimes no) means to recover itself the communication
- The ground geolocation is often the only way to understand who is the interferer
  - If it’s a broken station : the station is disconnected
  - If it’s a real jammer, a complaint is filed to the ITU (International Telecom Union)

Signal recovery – Steerable antenna

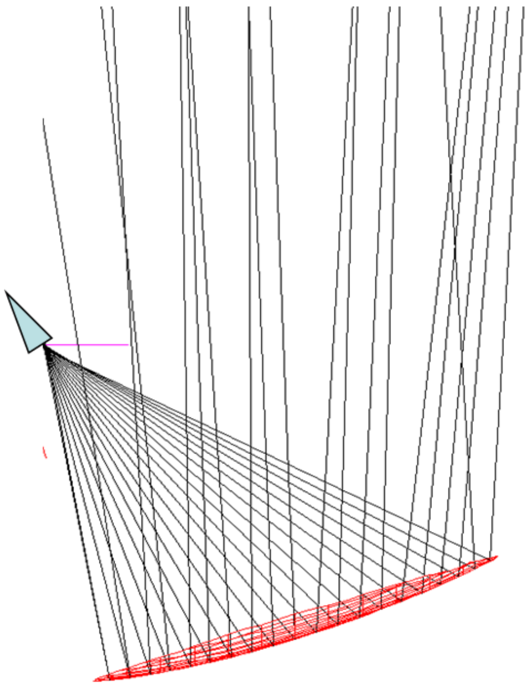
- Some bent pipes payload have steerable antennas
  - We can steer the reflector to decrease the gain at the interfer direction



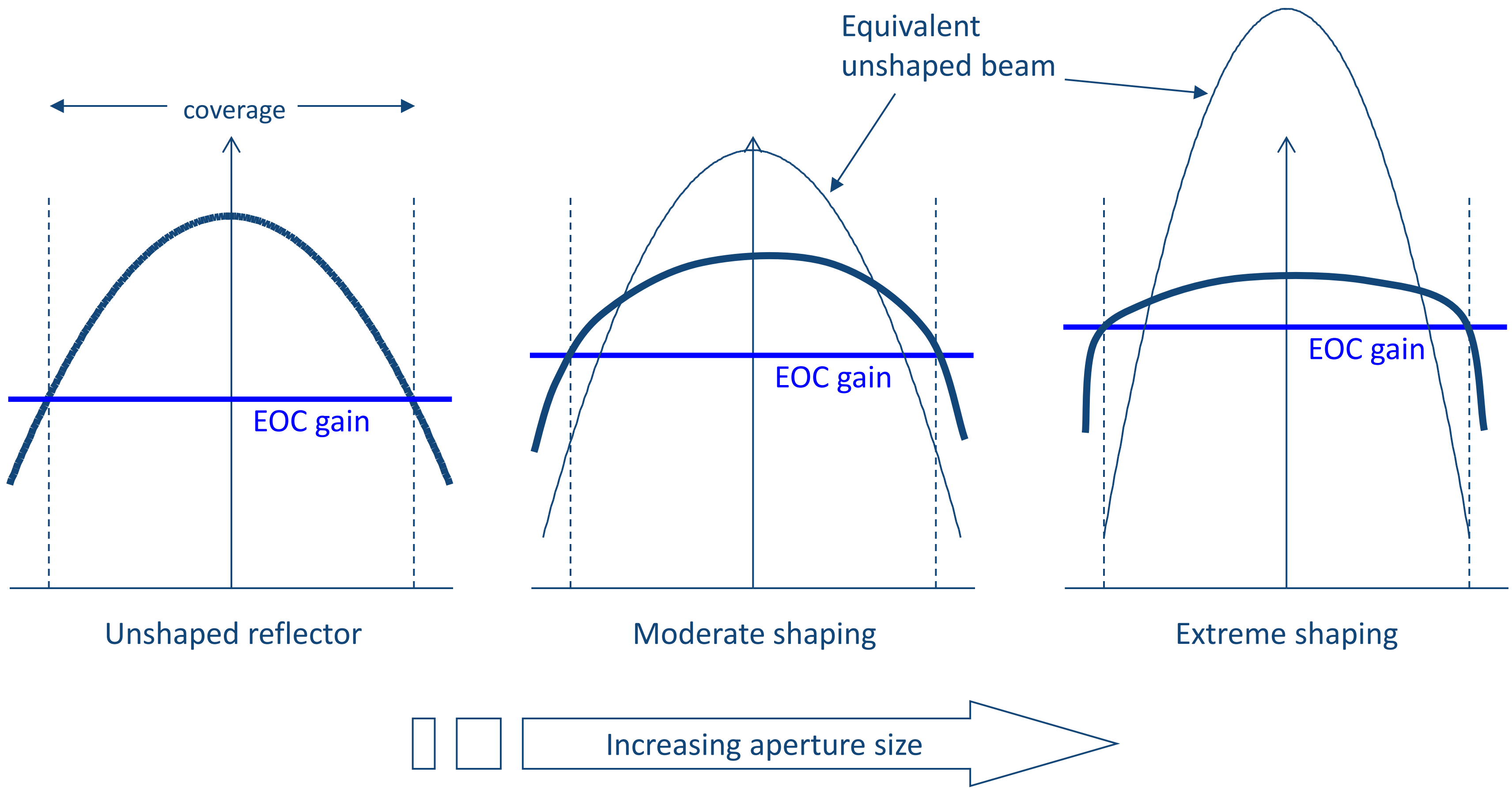
Signal recovery – Antenna shaping for isolation

- Some areas are known to be active in jamming
- The antenna can be designed to have a very low gain over a specific area
  - Use of shaped reflector to create complex contours
  - Increase of the reflector size to get sharp slope (see next slide)

Non-parallel reflected rays due to shaping



Shaped refector (quite extrem)



Need to increase aperture size to get more isolation on specific areas
Especially If they are geographically closed to the useful area

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Multibeam architectures

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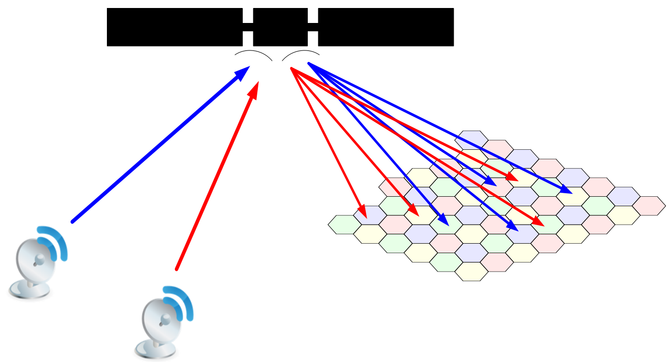
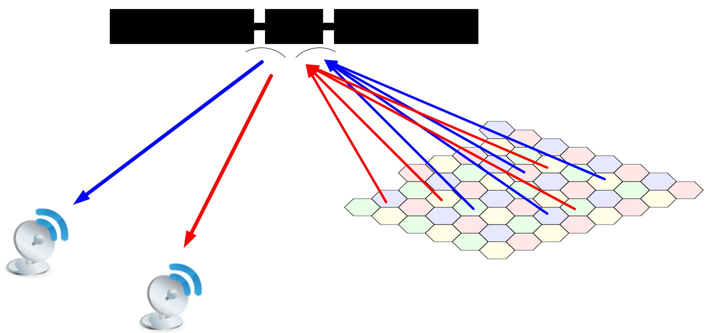
Multibeam payloads – System Architecture

- Instead to have one big coverage with the full frequency plan
- Several small coverages with a part of the frequency plan in each beam
  - Increase the capacity
  - Capacity = number of beams × capacity per beam
- Typically : around one hundred of beams
- One gateway is linked to a part of the beams
- Done for internet

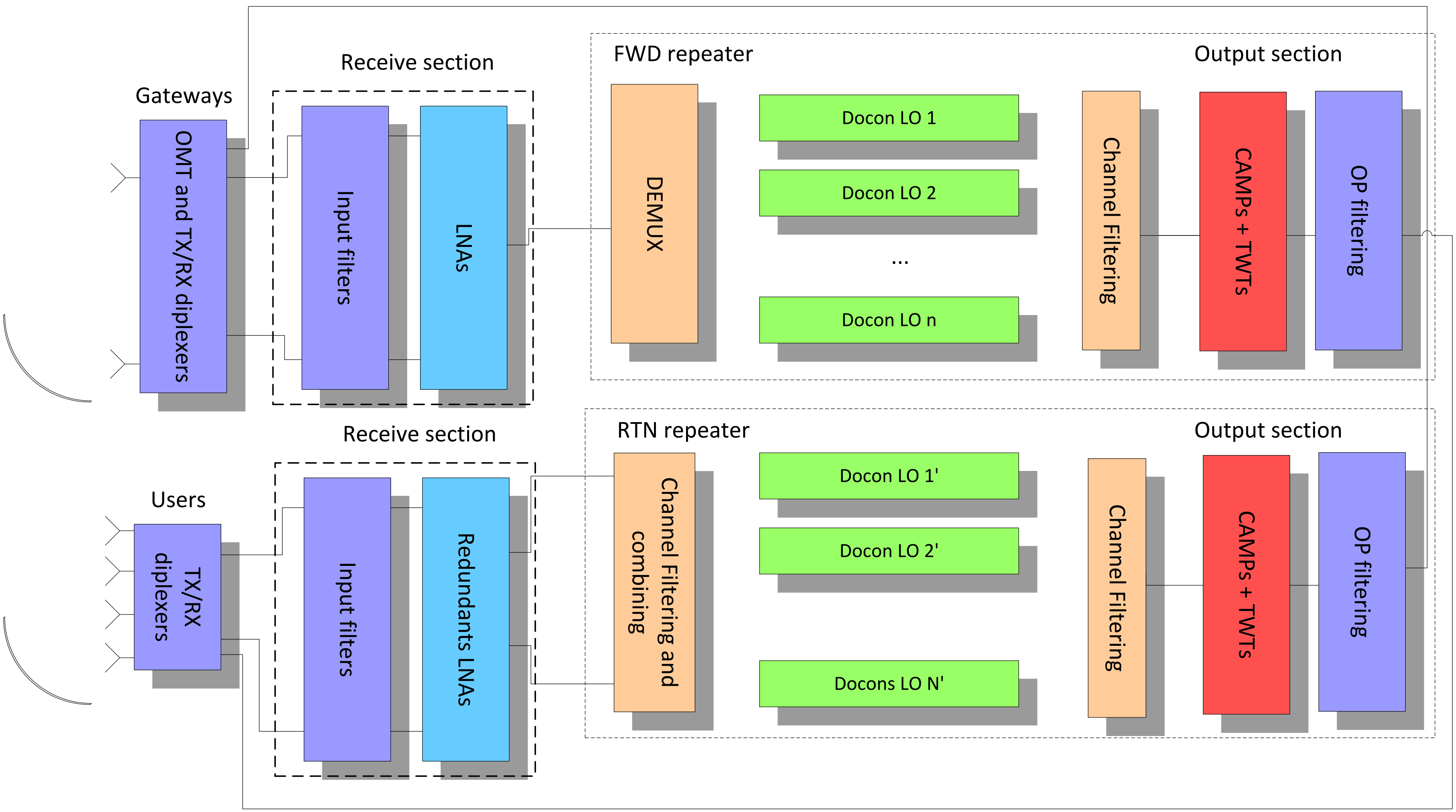


FORWARD LINK
Gateways to users



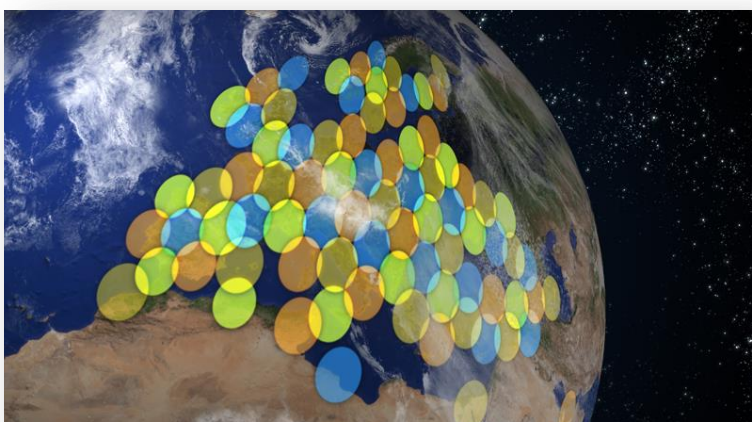
RETURN LINK
Users to Gateways

Multibeam payloads – Payload Architecture

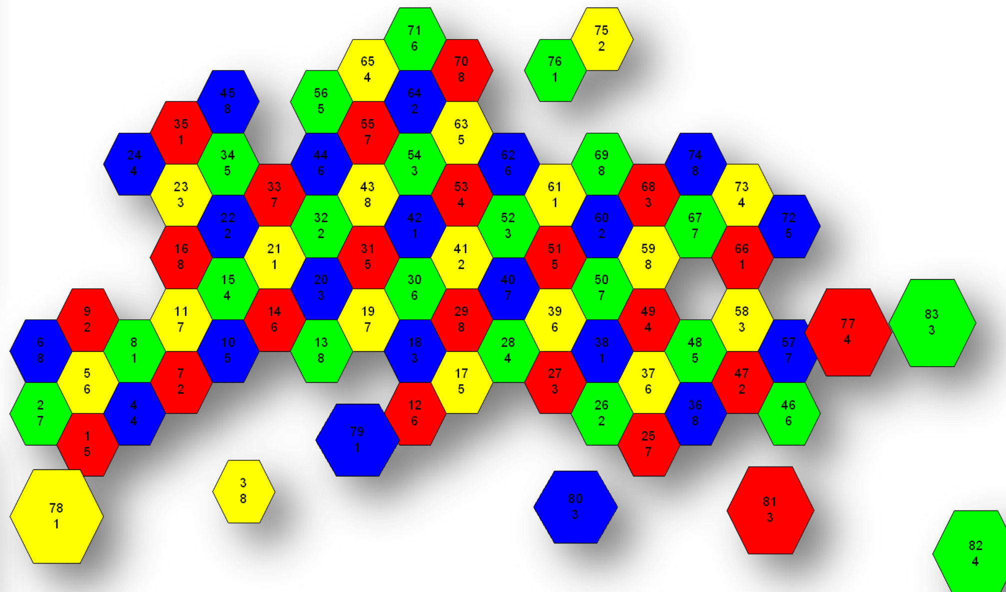


Multibeam payloads – Example : Ka sat

Ka Sat in anechoic chamber



Ka Sat beam layout



Ka Sat beam layout
With beam to Gateway mapping

Multibeam systems : Strengths and weaknesses

- All beams are very directive :
  - Only the neighbours beams can be jammed
  - Nearly impossible to jam the full system
- High EIRP jammers required for the Forward Link
- But the Return link is weaker as it has been designed for small terminals
- Difficult to detect jamming on the Forward link as there is not necesseraly a station in the jammed beam

Detection

- Detection of interferences on a multibeam classical architecture is more complex
  - Most of the beams doesn’t have ground station
  - If an interference occurs, the feedback is often done by the customer (loss of service) → slow reaction
- Can be solved by adding on-board complexity (like a processor) to do on-board spectrum analysis
  - Set several sub channels on the OBSA (On Board Spectrum Analyser). Setting done by Telecommand. Can’t do the full BW instantaneously
  - Results are sent to the ground via Telemetry

On ground geolocation system

- Multibeam architectures are not favorable to on-ground geolocation systems
  - Nearly no chance to have a mirror satellite with a similar beam at the same frequency
  - Multibeam are more frequent in Ka band with even less chance to get a mirror satellite (mostly in Ku band)

- The on ground geolocation system is limited to the observation of the beams. Not very accurate (~ beam size / 2)

Carrier ID

- Created to find the source of interference in case of non-intentional interference

- Carrier ID superimposes a signature on a satellite uplink signal, which allows satellite operators to identify the source of an interfering carrier. This is injected into the signal by the modulator, which creates two carriers the primary payload carrier and a low-power spread-spectrum CID signal

- Carrier ID modems are developped by Newtec. This system has been pushed by Eutelasat

Carrier ID – Implementation

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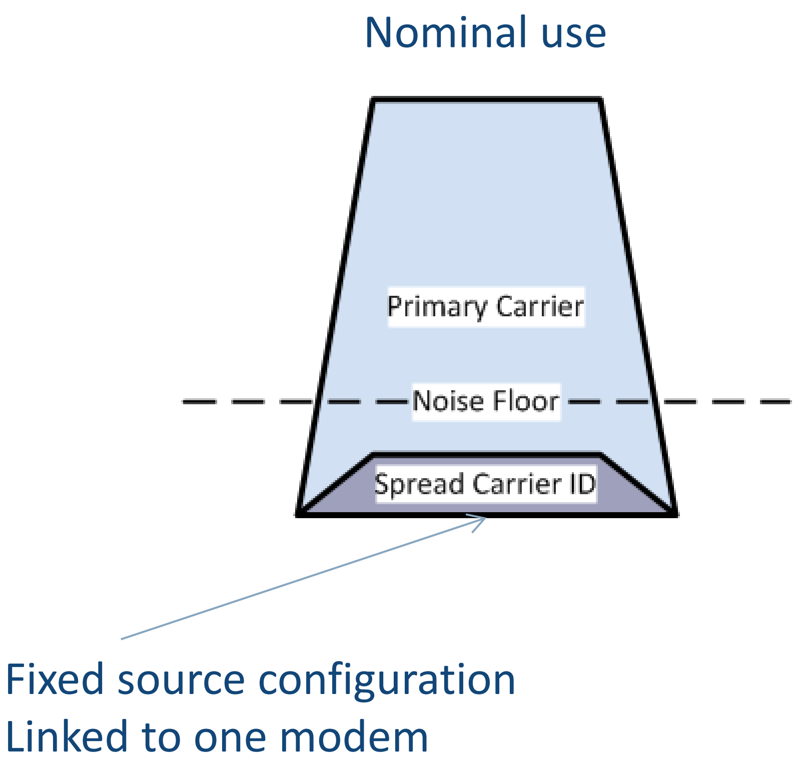
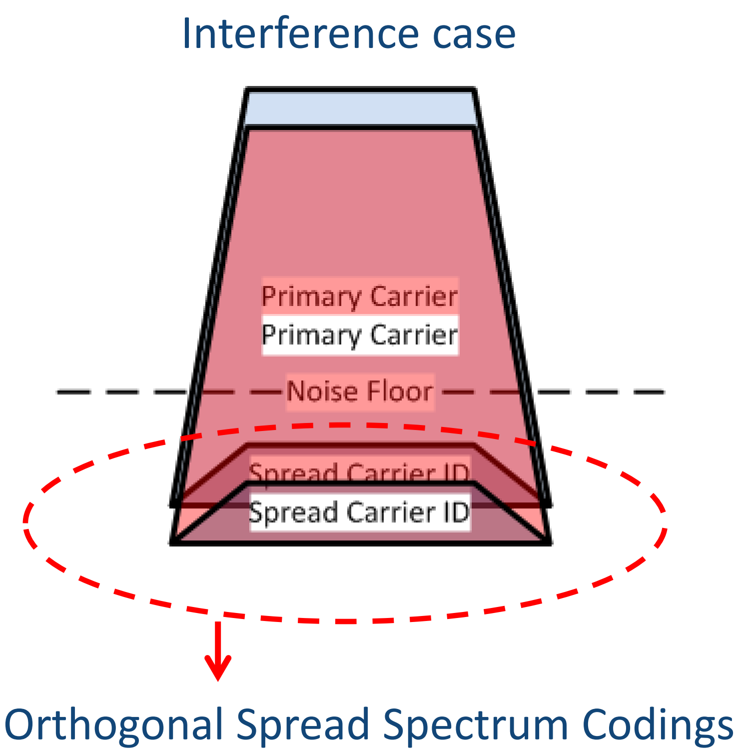
Carrier ID


Nominal use
Primary Carrier
Noise Floor
Spread Carrier ID
Fixed source configuration
Linked to one modem


Interference case
Primary Carrier
Primary Carrier
Noise Floor
Spread Carrier ID
Spread Carrier ID
Orthogonal Spread Spectrum Codings

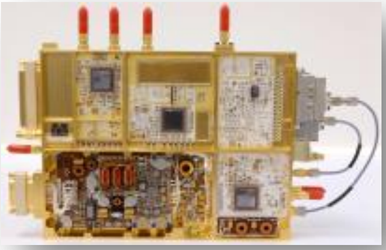
Multibeam – Improving (and complexifying) the payload design for better antijamming performances

- Classical multibeam architecture resist quite well to jamming
- But if a part of the mission is jammed
  - Difficult to detect
  - Difficult to geolocalise
  - Nearly impossible to recover : impossible to steer the reflector as all the feed cluster will be steered
- Need to complexify the payload
  - Analogue way : Flexible converters
  - Digital way : Introduction of processor

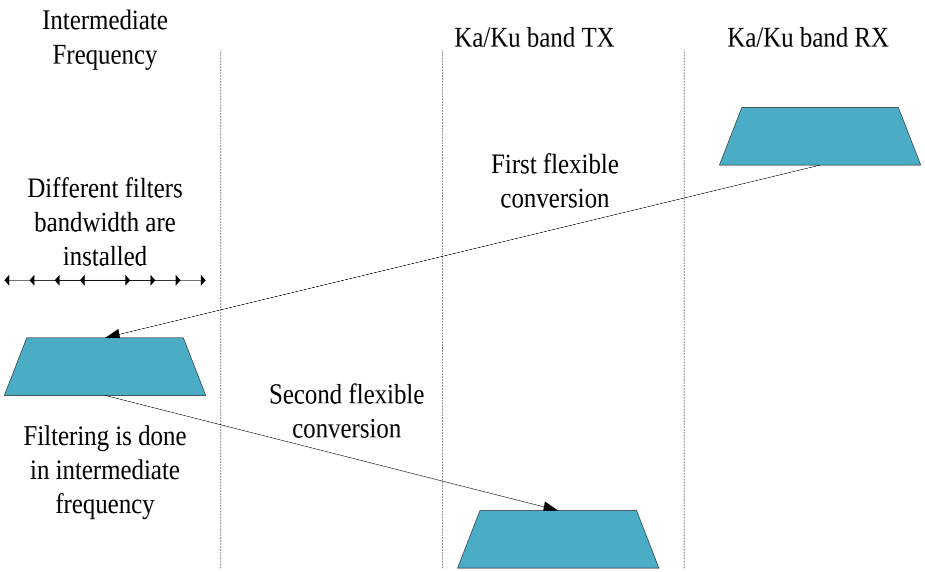
Agile converter – Example of the ACE

- The Agile Channel Converter Equipment (ACE) is from an operator point of view a flexible Ka to Ka or Ku to Ku converters providing flexible filtering as well

- It provides the following capabilities:
- Flexible frequency translation
- Flexible channelization. Filter bandwidth selectable between 125, 250, 375 and 500MHz for forward link and 31.25, 62.5, 125 and 250MHz for return link
- Flexible channel center frequency
- Variable gain



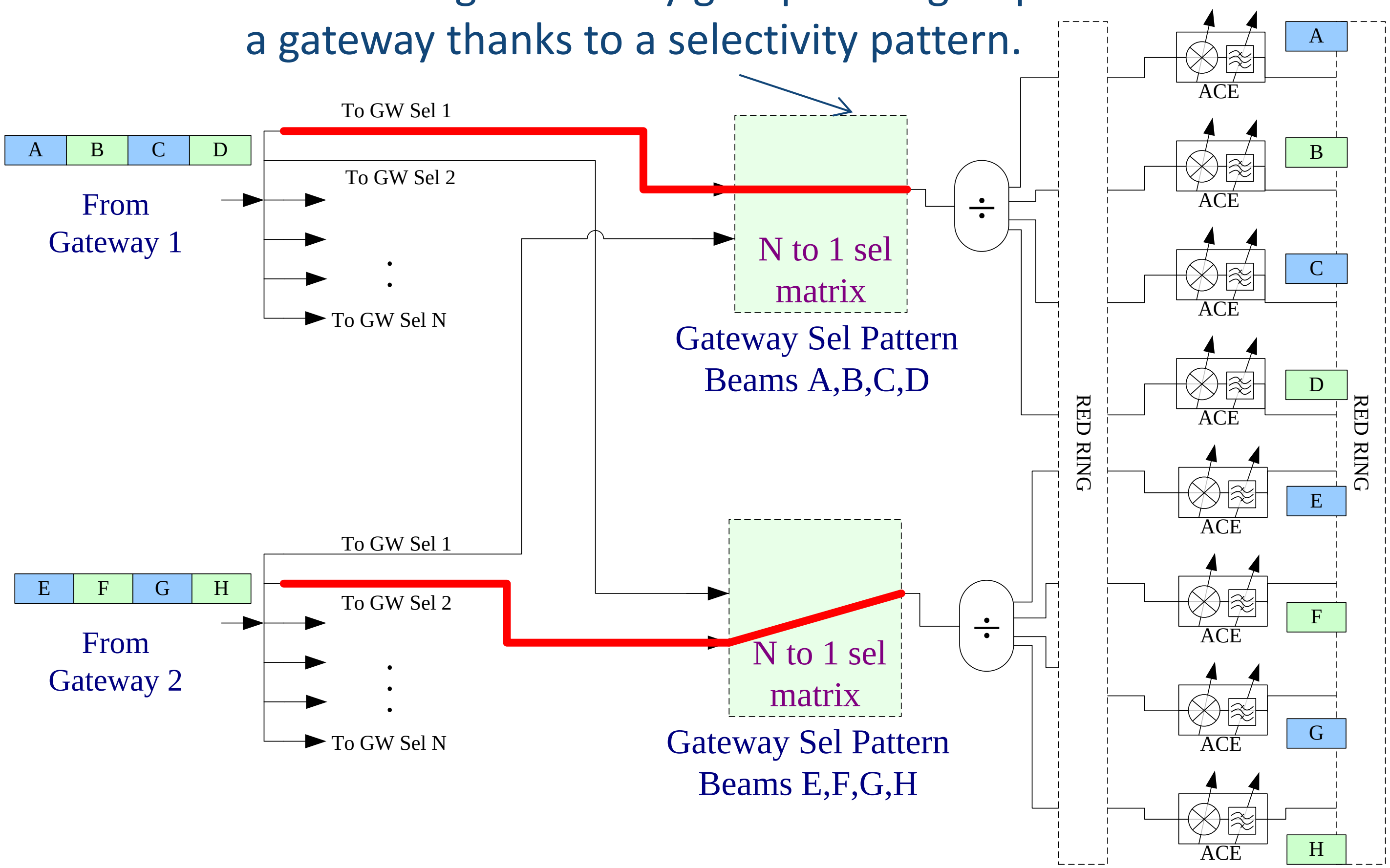
Current generation installed on Hylas and Quantum



Multibeam payload architecture – with Agile converter

- The following figure shows how to implement this equipement in a multibeam architecture

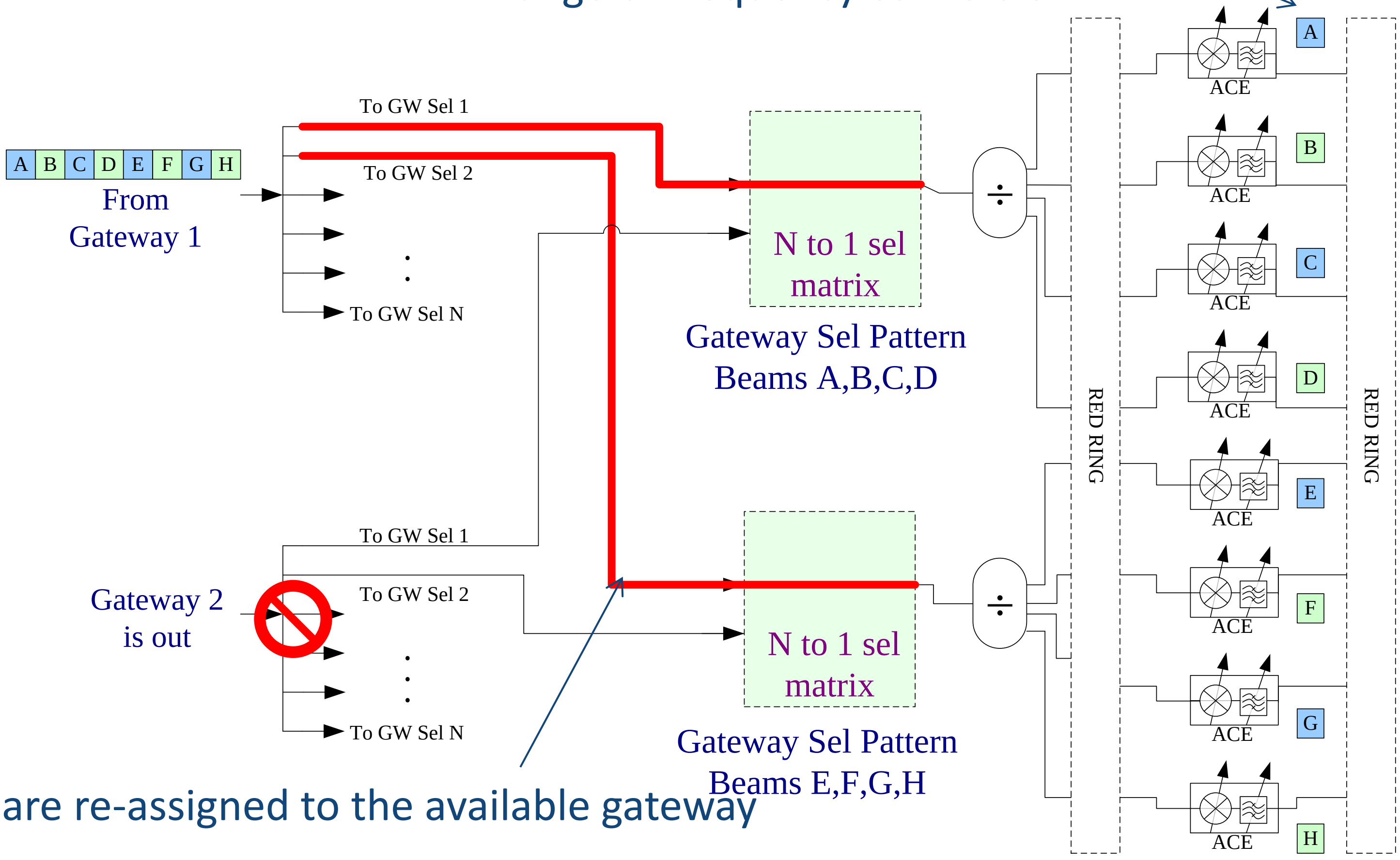
Beams are gathered by group. Each group access a gateway thanks to a selectivity pattern.



Multibeam payload architecture – with Agile converter – jamming case

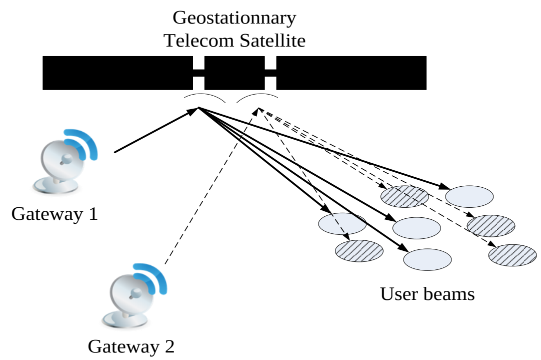
Changing ACE setting

- Change of filter
- Change of frequency conversion

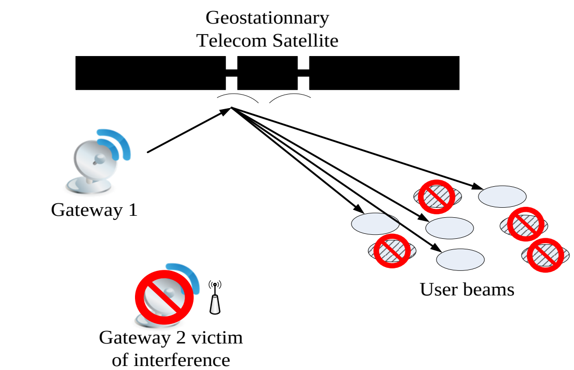


Beams are re-assigned to the available gateway

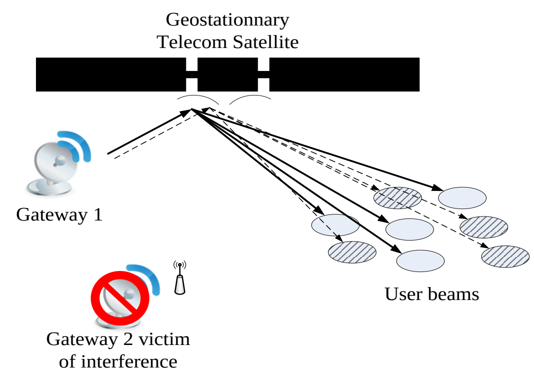
Multibeam payloads – Gateway mitigation by beam/gateway re-assignement



Step 1 : all gatweways are available



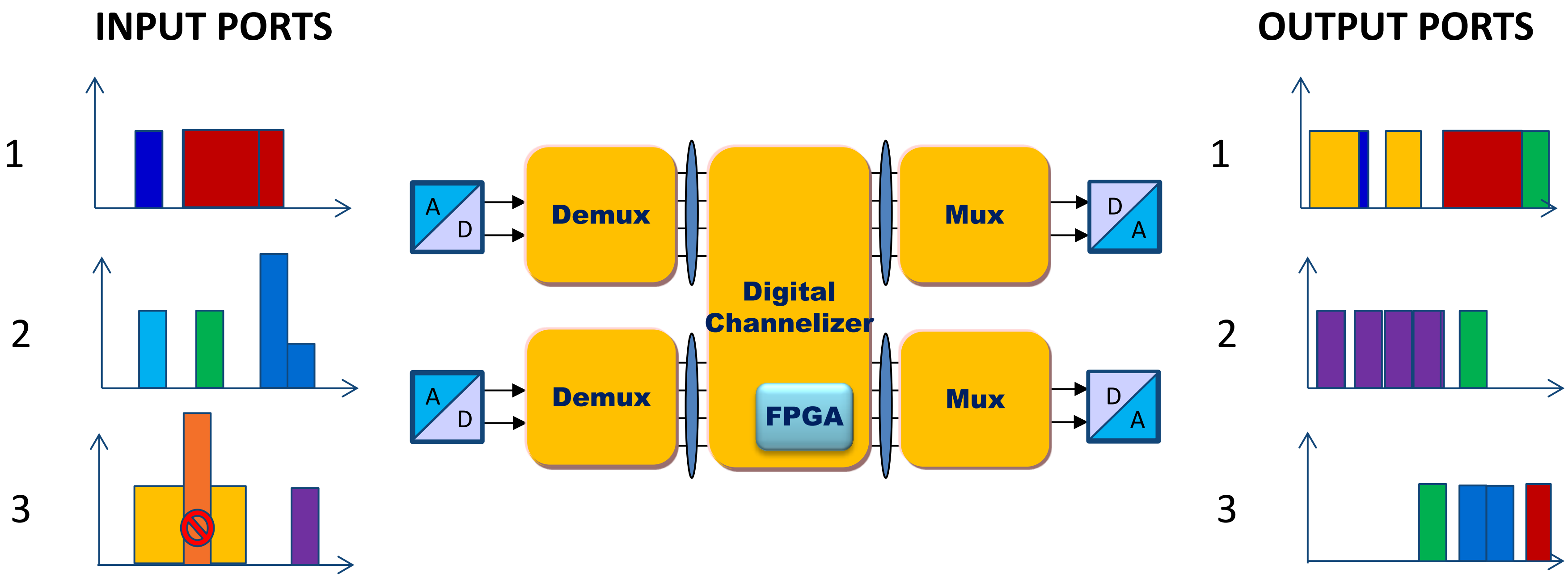
Step 2 : Gateway 2 is jammed. Beams linked to gateway 2 are unavailable



Step 3 : Reassignement of beams to gateway 1. All beams are available

Alternative solution to the classical one with better resistance to jamming

Processors - Capabilities

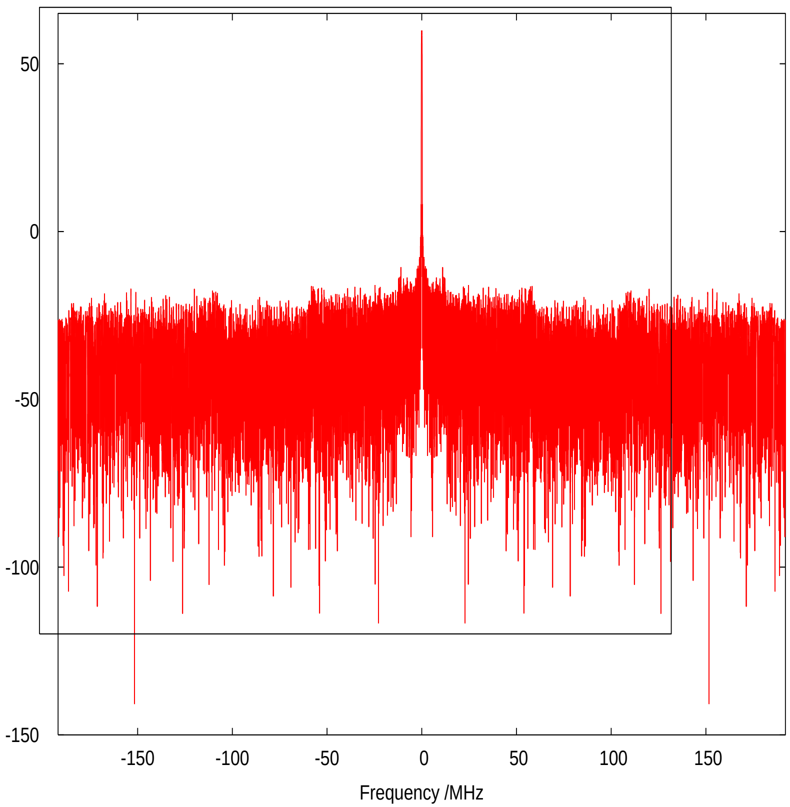


- ❑ Fine frequency channelization
- ❑ From any input to any output
- ❑ From any frequency to any frequency
- ❑ Multicast
- ❑ ALC
- ❑ Blocking of unwanted channels
- ❑ Frequency hopping
- ❑ **FPGA Ready**
  - Interference mitigation
  - Geoloc
  - Regenerative Processing
  - Crypto…

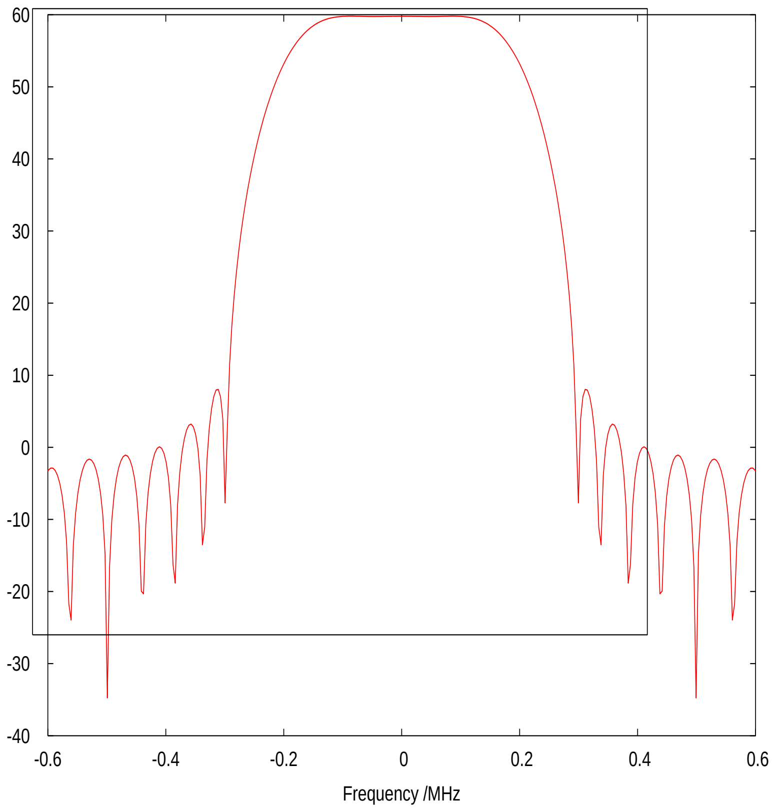
Processors – Sub channelisation

- The input bandwidth is demultiplexed into sub channels
  - The sub channel bandwidth depends on the processor generation and the frequency clocking of the ASIC
    - Around 333 kHz on the GEN3
    - Around 700 kHz on the GEN4
- The sub channel filter is very narrow
  - Interesting to remove unwanted signals and protect the output section of the payload

Processors – Sub channelisation



Filter response of one sub-channel



Zoom on passband

Processors – Measurement functions

- Available on several sub channels
- Measurements can be sent by Telemetries

On board spectrum analyzer

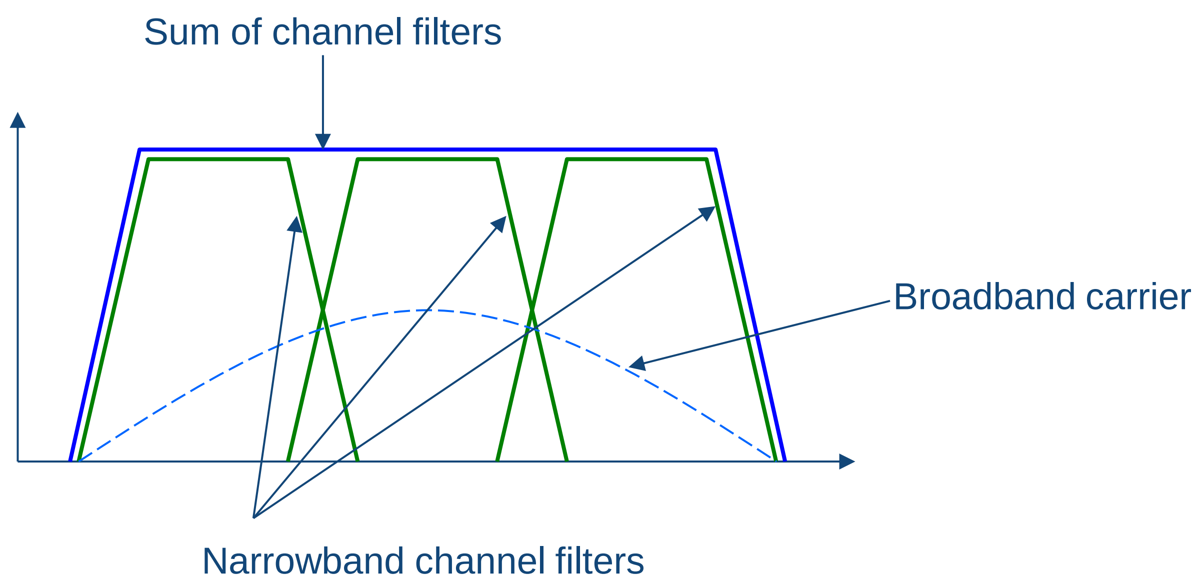
- In each sub channel, the processor can measure the power during a specific time range
- Can do smaller sub channel for this function specifically
- Provide to the ground a picture of the spectral density on each port

Correlation

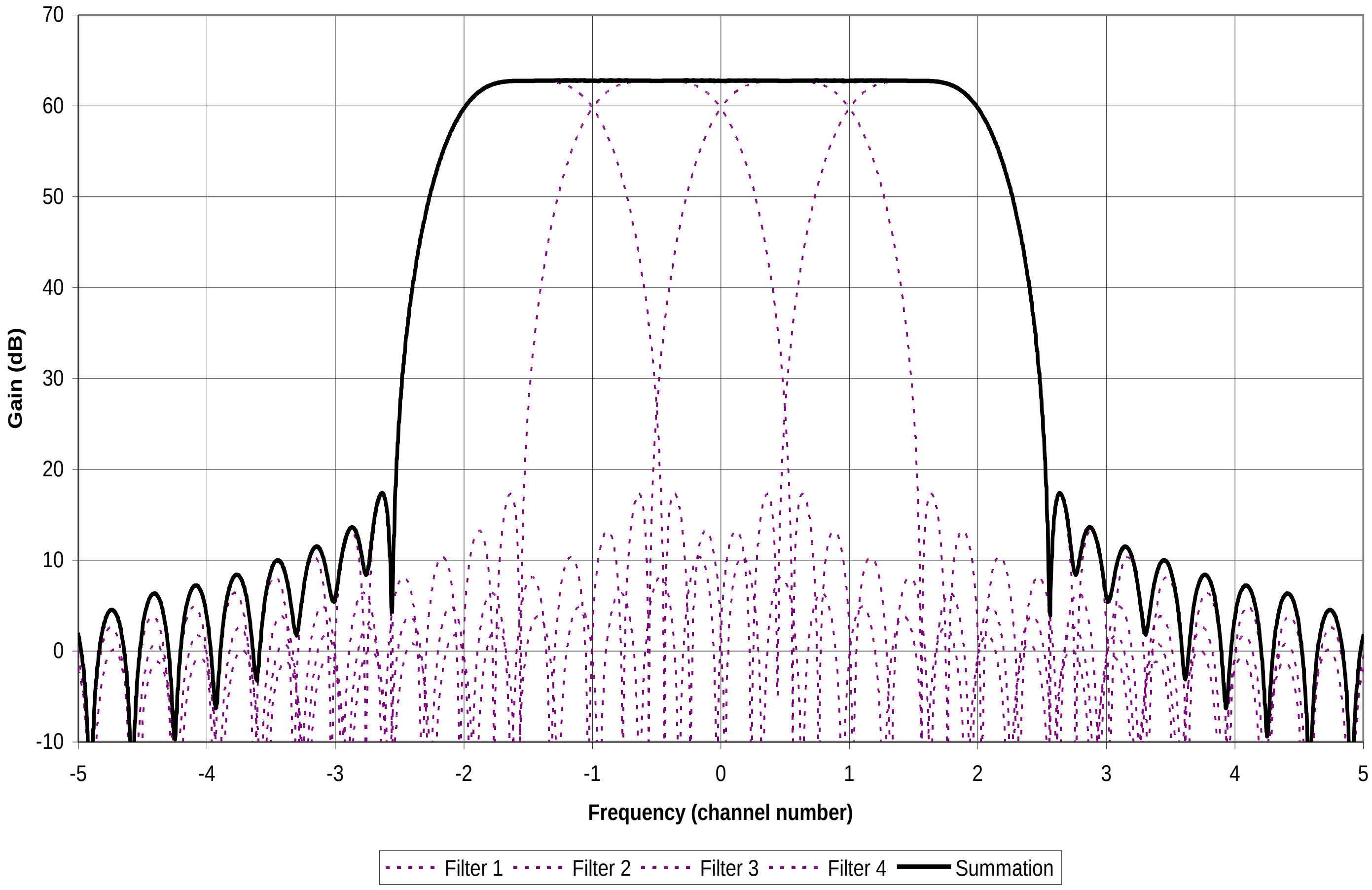
- Signals from two ports are correlated (any port to any port)
- Useful for calibration
- And useful for geolocation

Contiguous Channelisation

- A broadband carrier is demultiplexed into multiple constituent narrowband channels
- Constituent channels are routed & beamformed together
- The broadband carrier is reformed in the digital mux

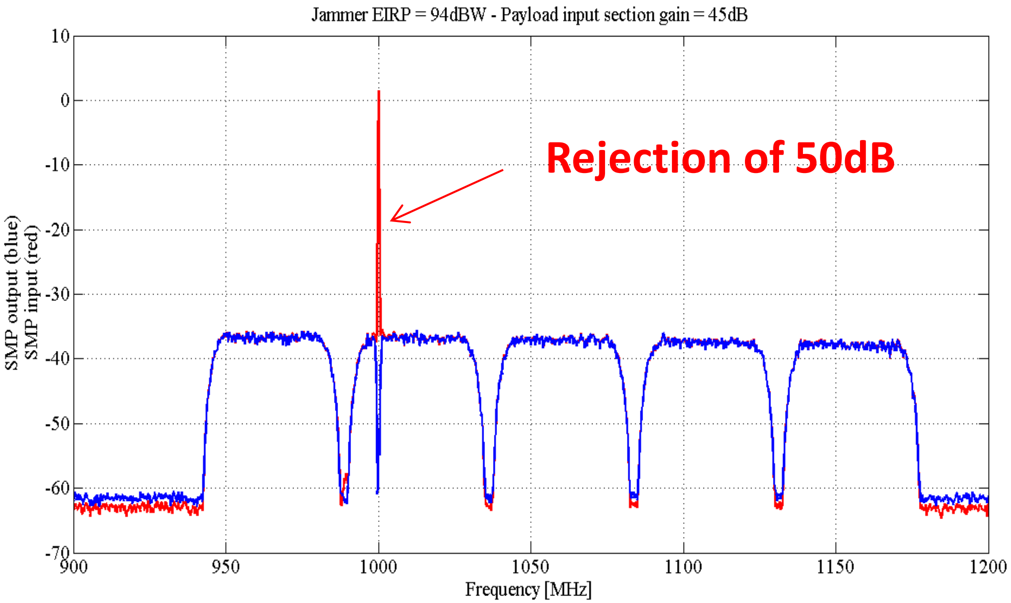


Example of Contiguous Channel Filter Design

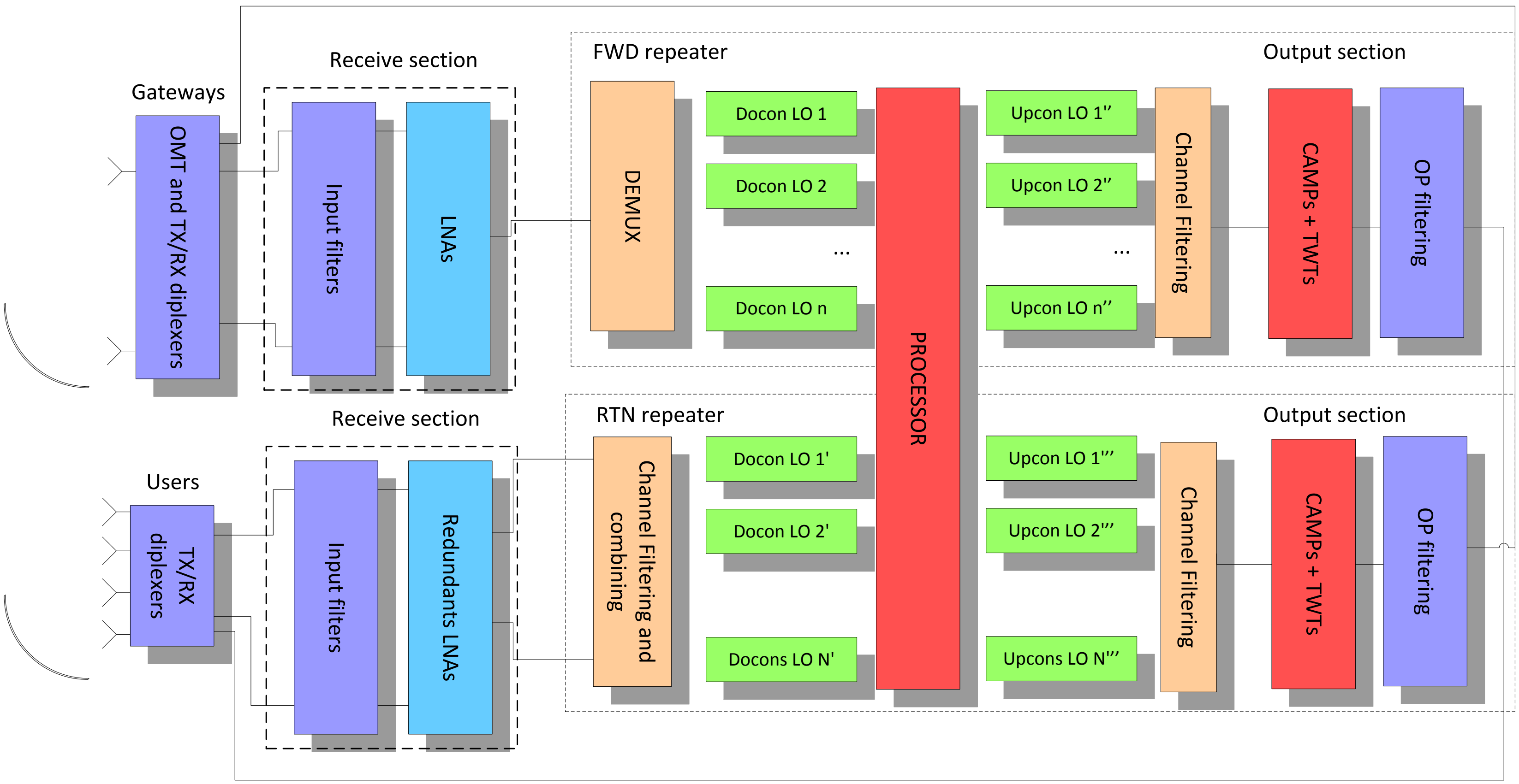


Processor – Sub channel removing

Possibility to remove the impacted sub-channels
•Works very well with signals that are static in frequency
•Uplink frequency plan can be re-ordered beside the nulled sub-channels without impact on the downlink frequency plan



Multibeam architecture – Single feed per beam antenna



Processor – Example SES 12 / SES 14

- The GEN3 processor (similar to Kmilsat) is on SES 12 and SES 14
- The full connectivity enables Gateway rollout
- The sub channel removing can protect the output section versus static CW jammer
- Only a part of the mission is processed
  - Hybrid architecture
- The other part is done with classical analogue equipments
- SES claims that their satellite have antijamming protection thanks to the processor
  - Not at the level of military satellite
  - But it shows that commercial customers are more and more interested by antijamming protection

GEN3 processor

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Frequency hopping

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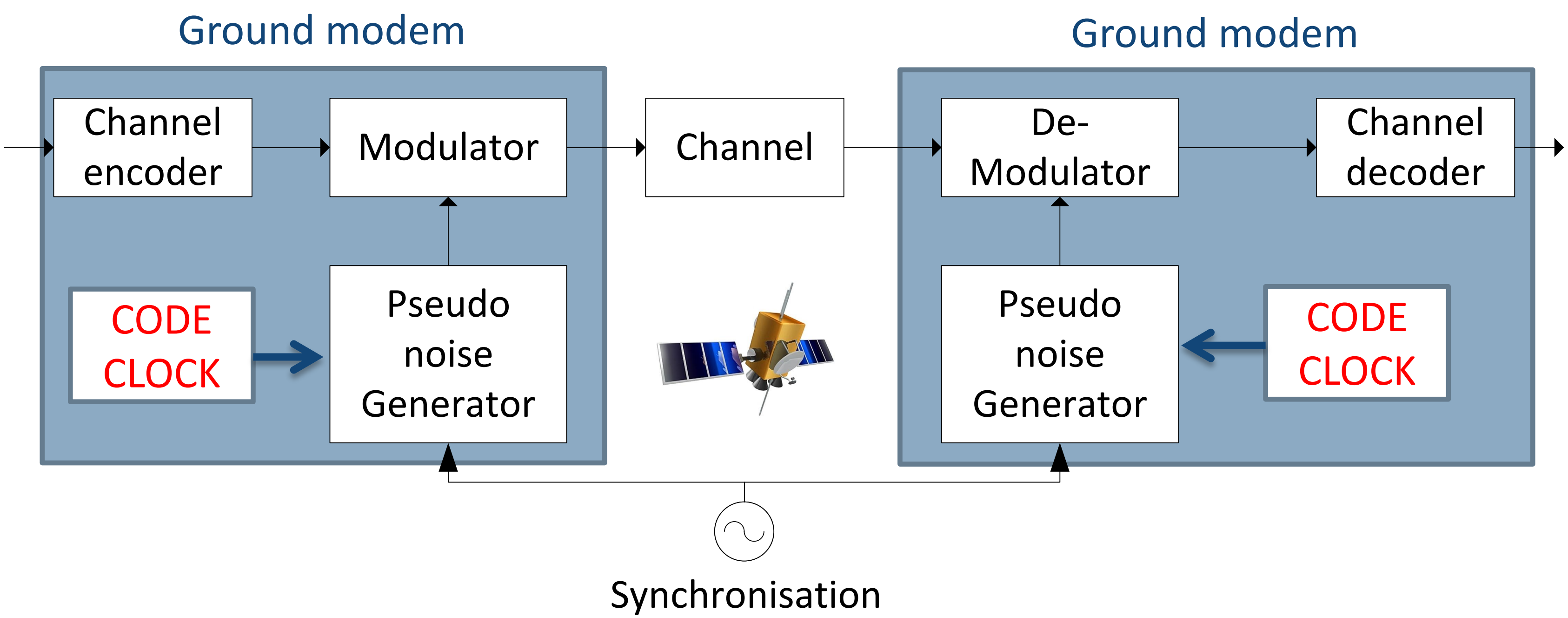
Frequency hopping

- The frequency hopping spread spectrum method is a method where the signals are
  - Emitted within many sub-channels
  - Switching from one sub-channel to another by following a pseudo random sequence
  - This sequence is known by the emitter and the transmitter

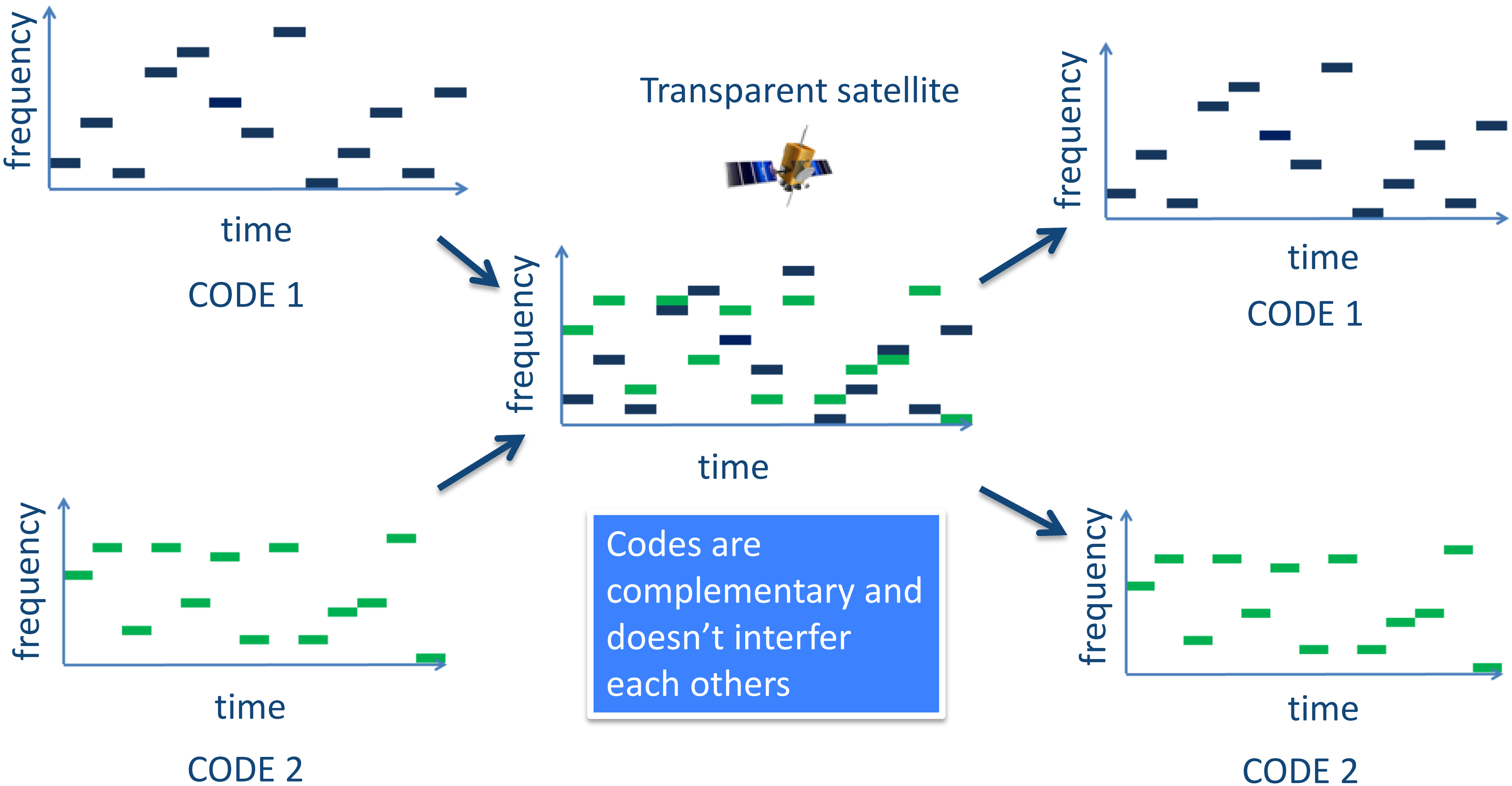
- On board dehop / rehop system will block all the signals that doesn’t follow the pseudo random sequence to protect the output section of the satellite

Frequency hopping – Classical system

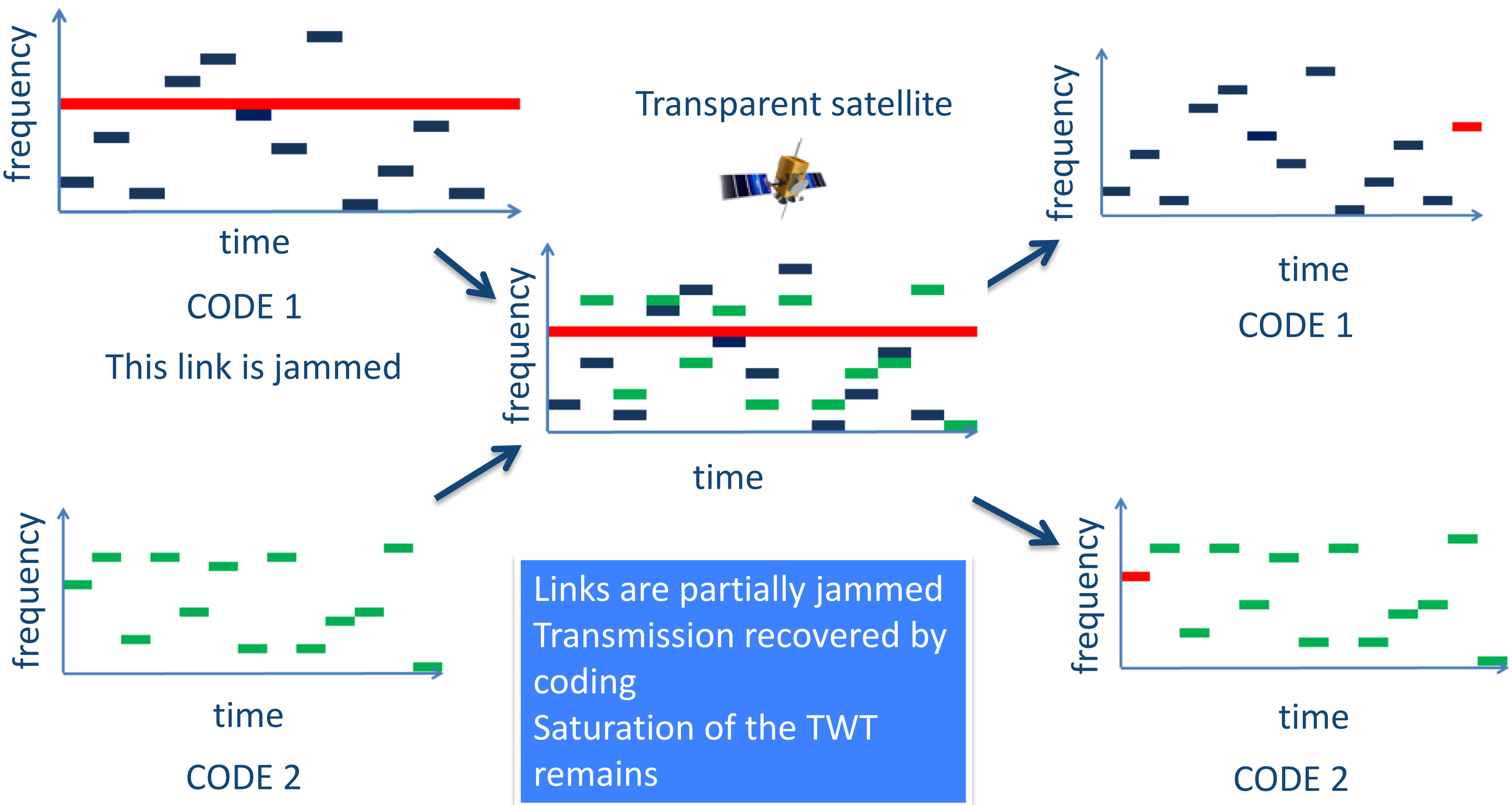


Typical implementation with transparent satellite
The satellite send a signal to the ground for the modem synchronisation wrt the Pseudo noise generator.
The TRANSEC sequence that generate this pseudo noise can be extremely long

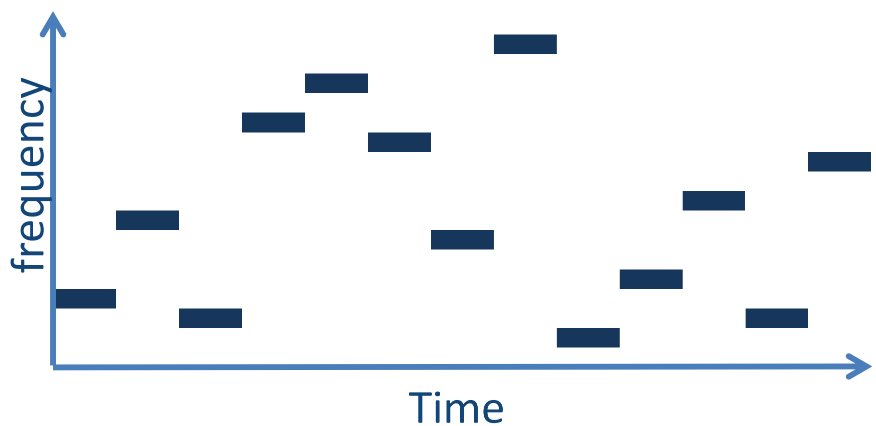
Frequency hopping – Complementary codes



Frequency hopping – Consequence of a jammer

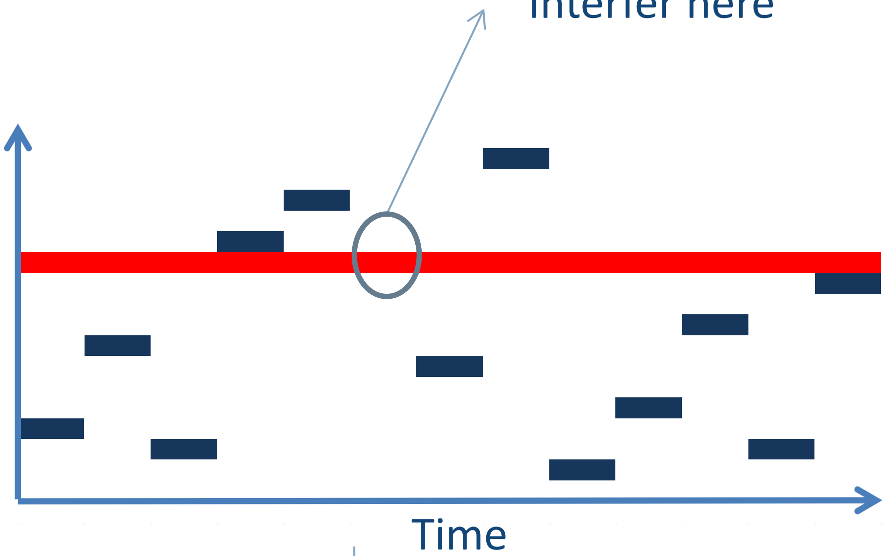


Frequency hopping : On board DeHop / ReHop



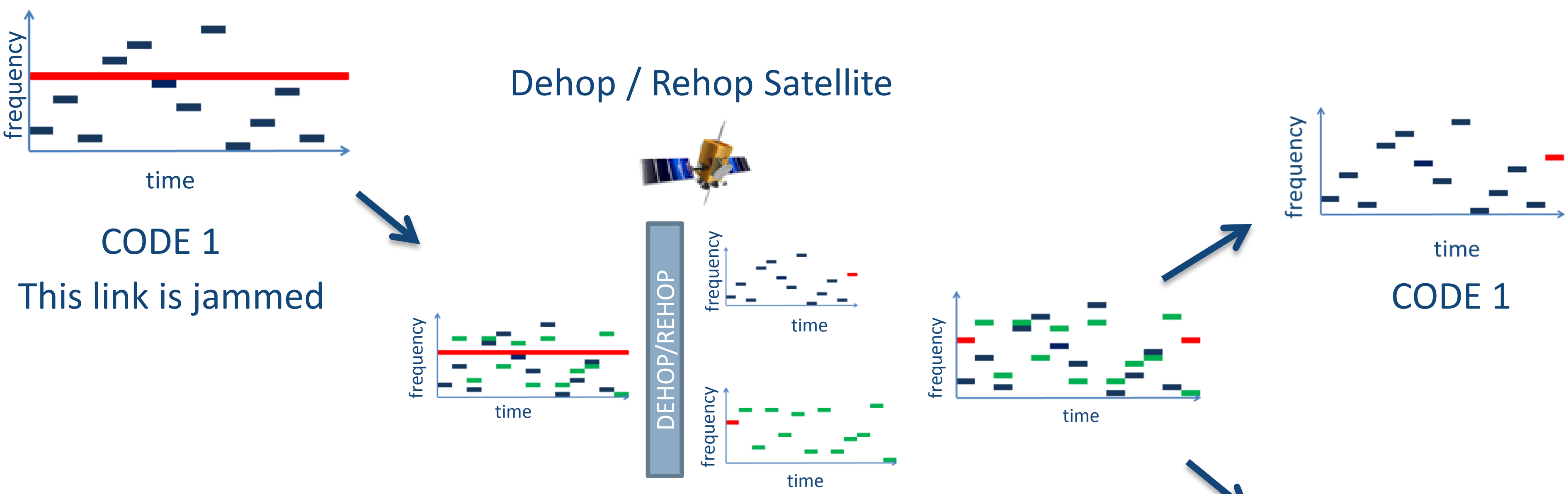
This is the sequence for the signal A
The other frequency/time slots are blocked

Interfer here



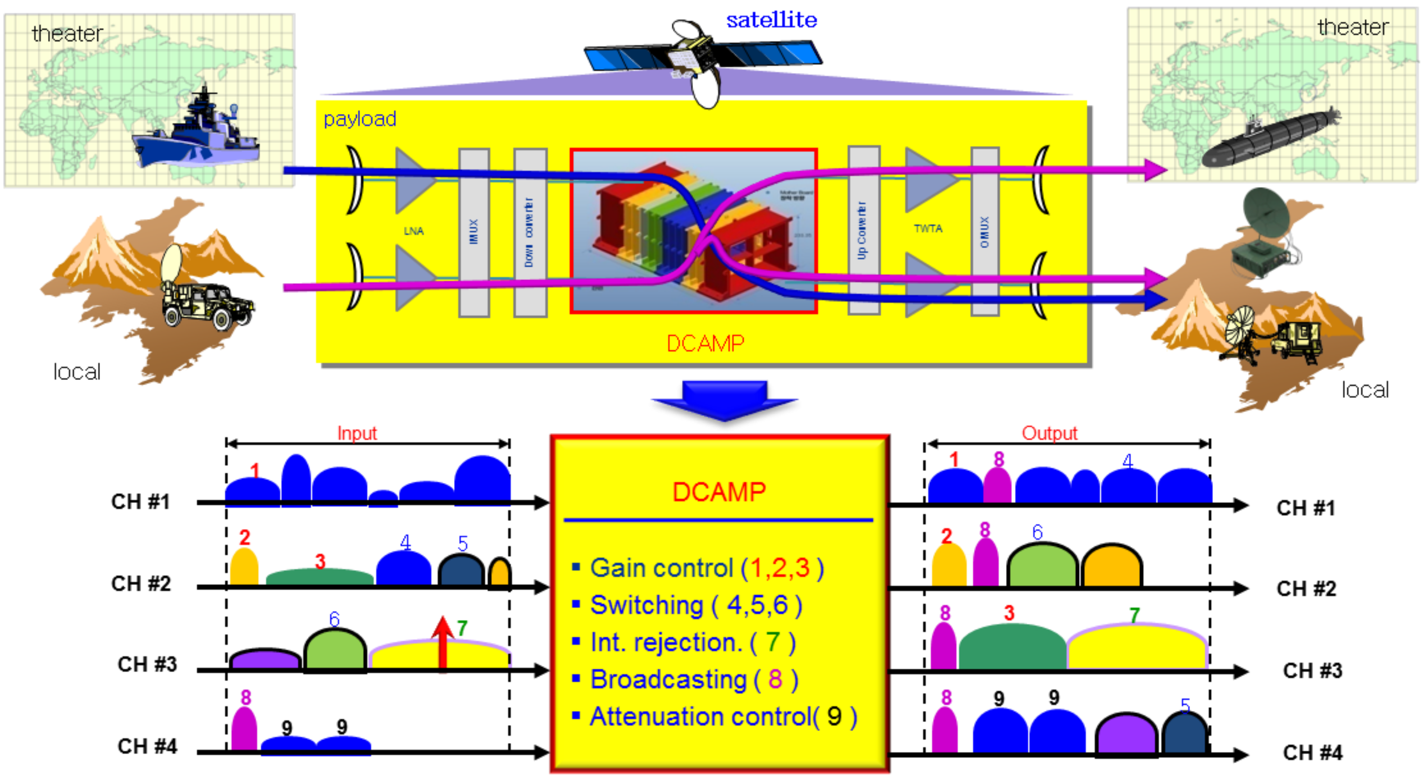
The jammer in red is not routed through the dehop / rehop system
It just interfers one time with the signal A
Lot of energy of the jammer has been rejected

Frequency hopping – Consequence of a jammer

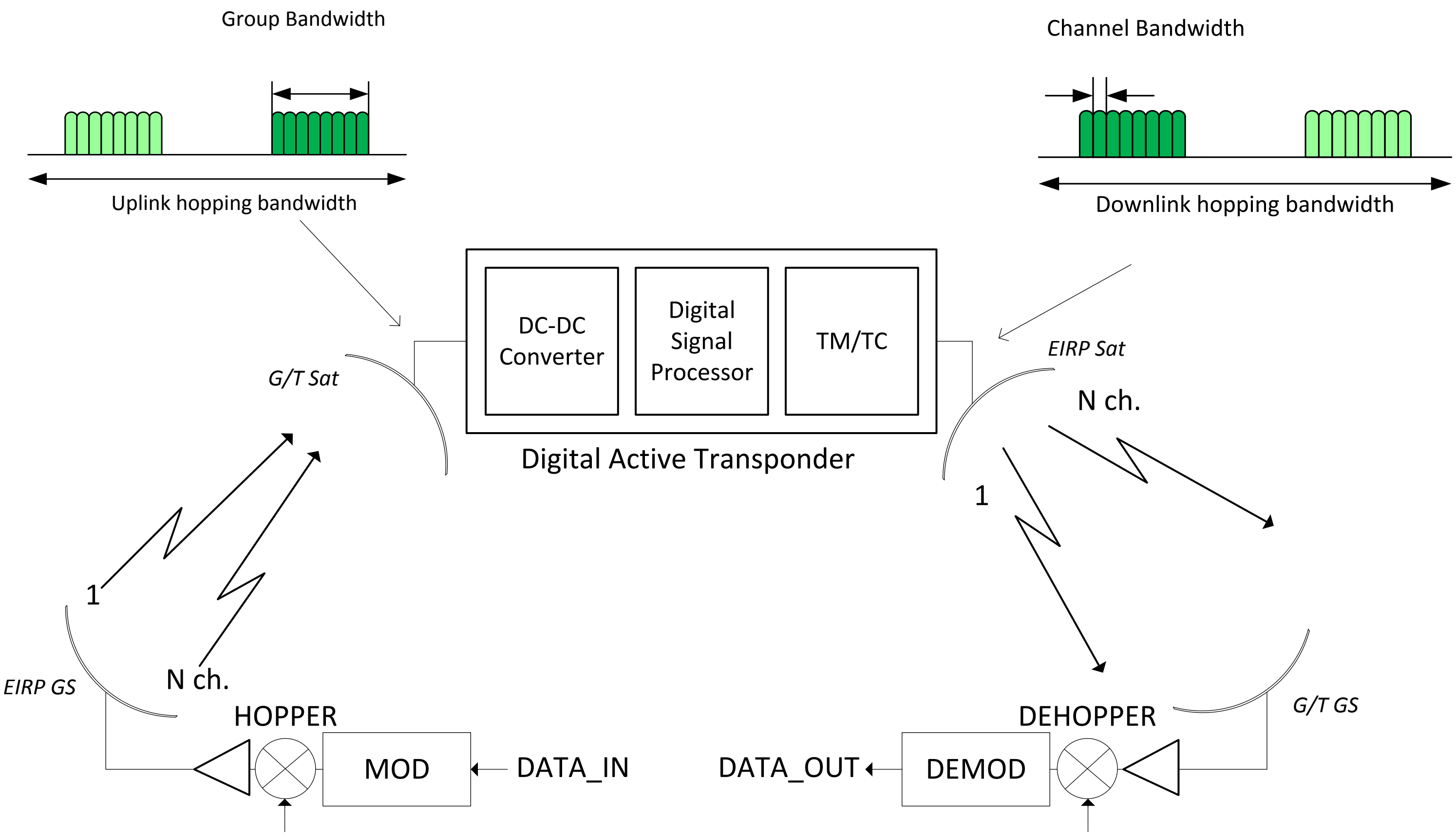


Links are partially jammed
Transmission recovered by coding
Jammer is removed in the DSP before the output section
TWTs are protected : No saturation effect

DCAMP functional

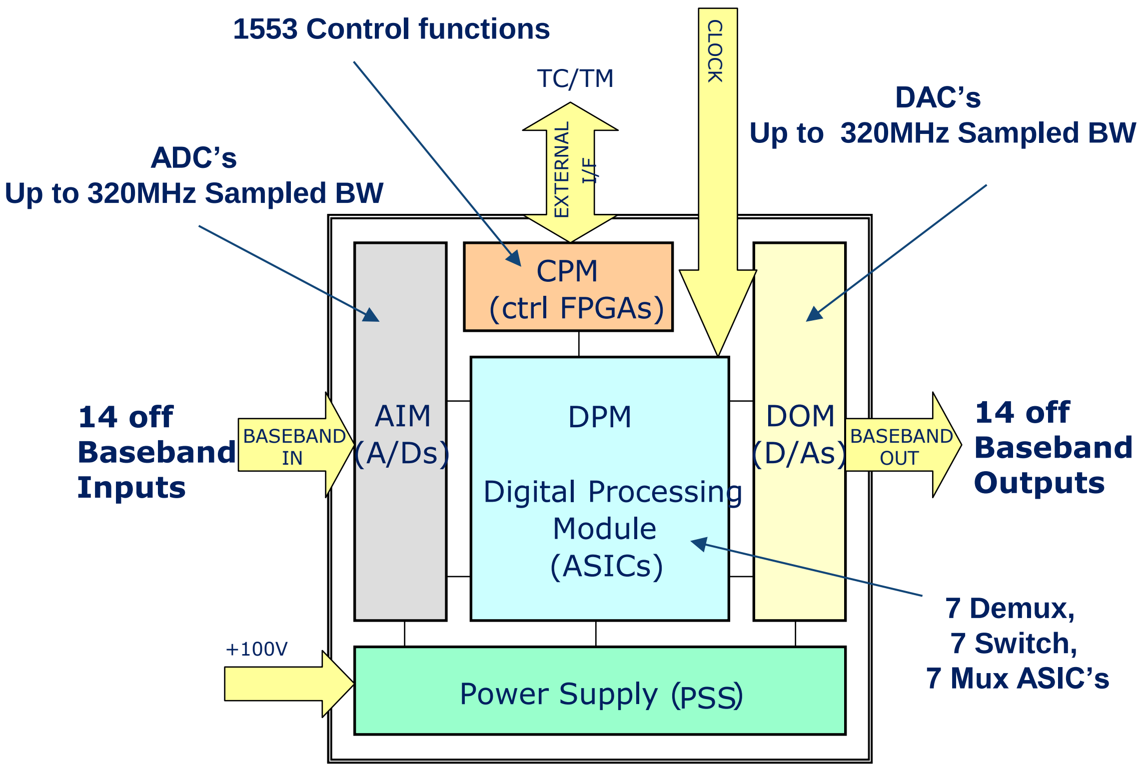


DAT concept

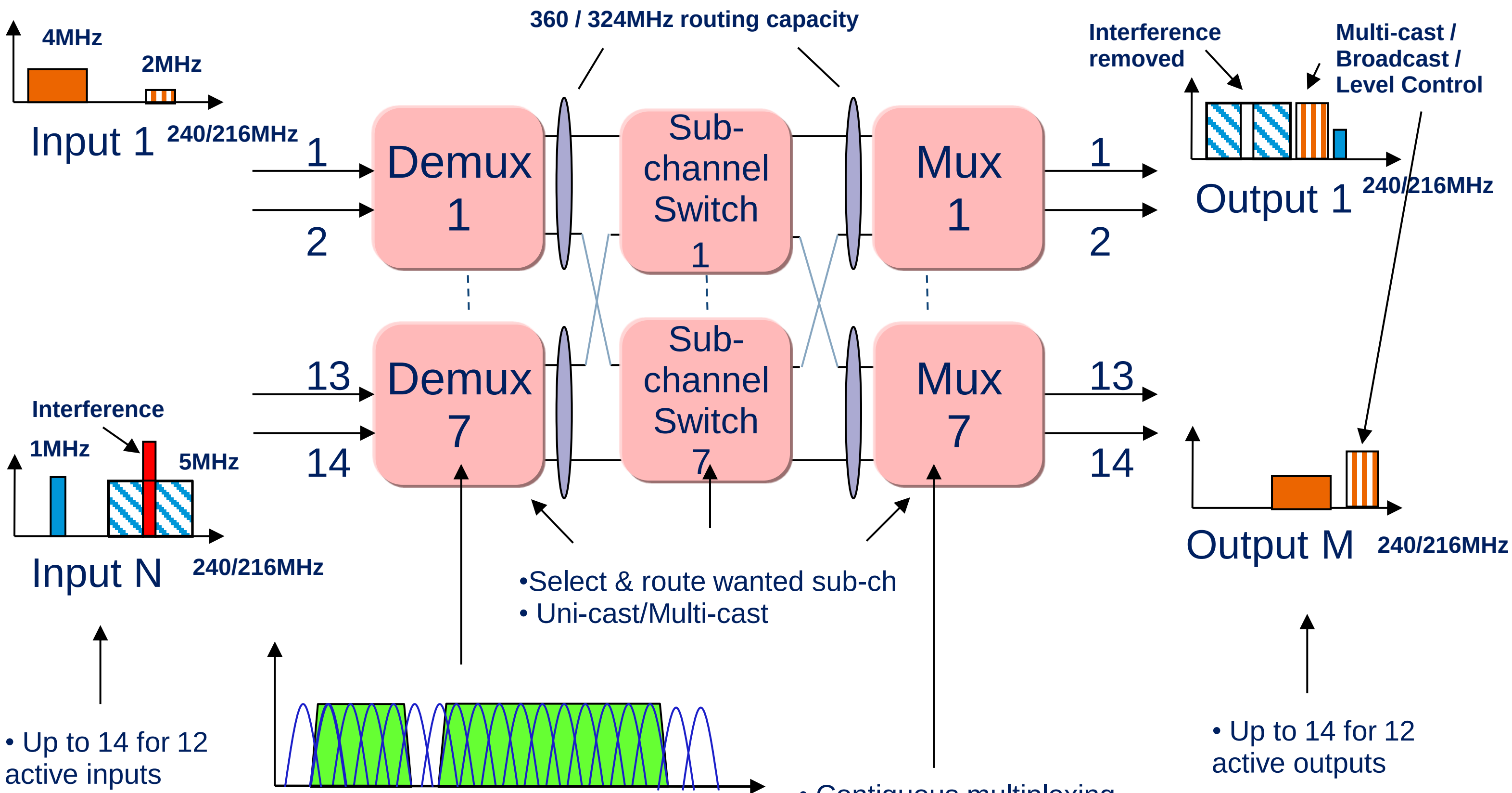


Digital Active Payload and MF-TDMA System Block Diagram

Gen 3 Broadband Channeliser



Gen 3 DCAMP Channeliser (with Tight Filtering)



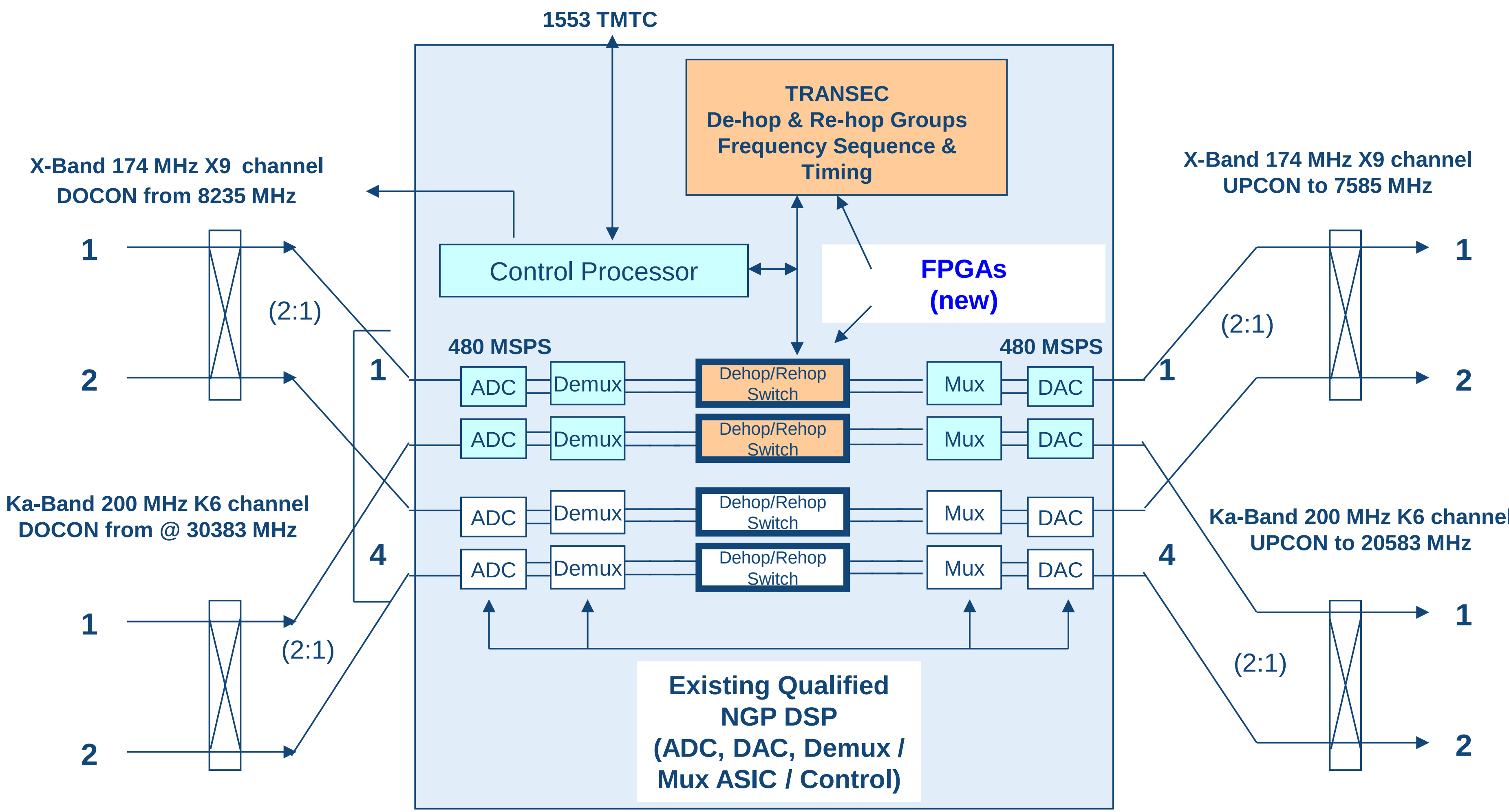
- Up to 14 for 12 active inputs
- **Average** 180/162MHz bandwidth routable per input

- Contiguous demultiplexing based on 250/225 kHz granularity
- 48 dB fixed gain / ALC
- Power measurement
- Interference removal

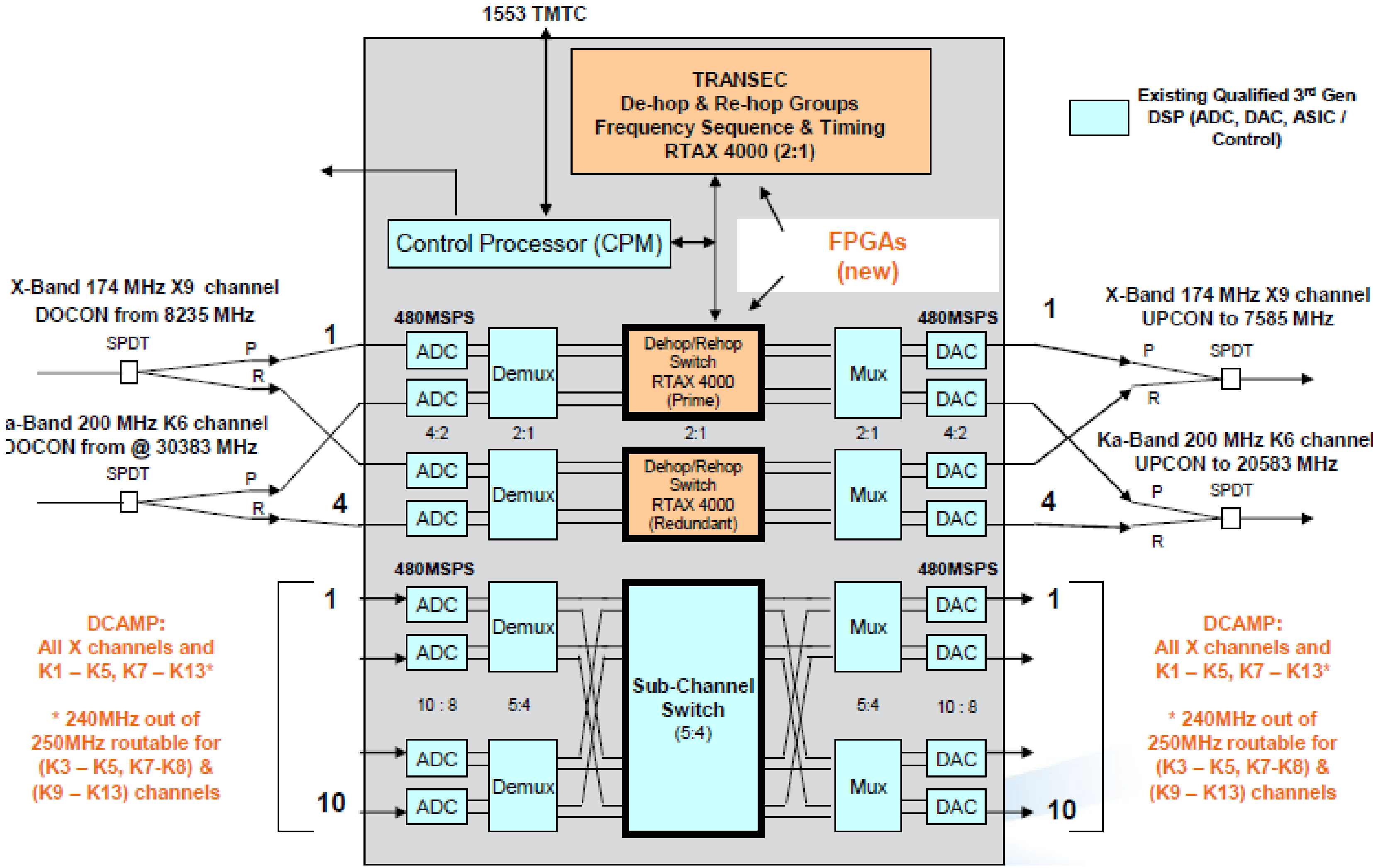
- Contiguous multiplexing based on 250/225 kHz granularity
- 48 dB fixed gain / ALC
- Power measurement

- Up to 14 for 12 active outputs
- **Average** 180/162MHz bandwidth routable per output

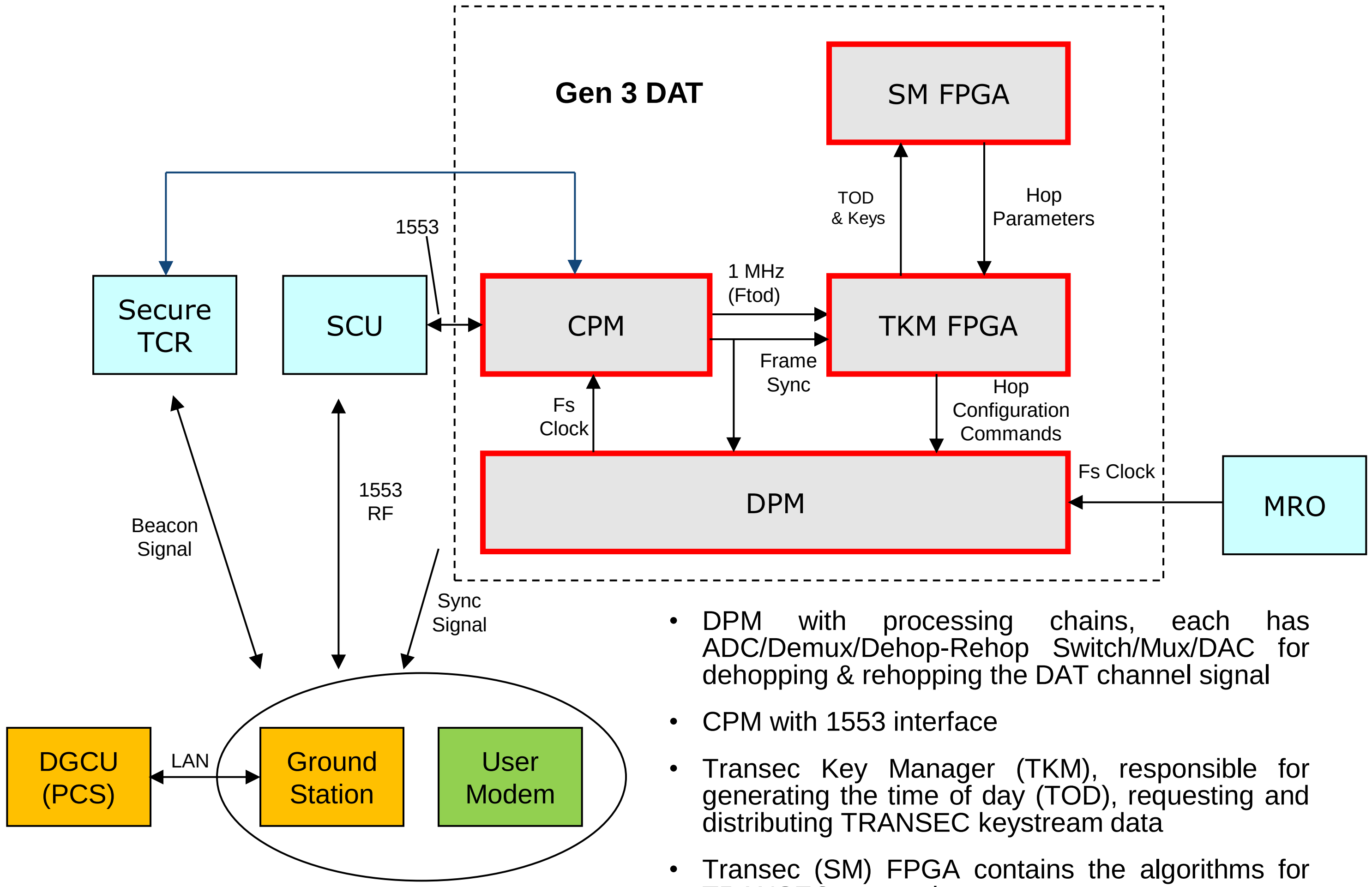
X/Ka DAT Processor Functional Blocks



Details


1553 TMTC
TRANSEC
De-hop & Re-hop Groups
Frequency Sequence & Timing
RTAX 4000 (2:1)
Existing Qualified 3rd Gen DSP (ADC, DAC, ASIC / Control)
Control Processor (CPM)
FPGAs (new)
X-Band 174 MHz X9 channel
DOCON from 8235 MHz
SPDT
P
R
1
a-Band 200 MHz K6 channel
DOCON from @ 30383 MHz
SPDT
P
R
4
480MSPS
ADC
Demux
Dehop/Rehop Switch RTAX 4000 (Prime)
Mux
DAC
4:2
2:1
2:1
2:1
4:2
Dehop/Rehop Switch RTAX 4000 (Redundant)
X-Band 174 MHz X9 channel
UPCON to 7585 MHz
Ka-Band 200 MHz K6 channel
UPCON to 20583 MHz
DCAMP:
All X channels and
K1 – K5, K7 – K13*
* 240MHz out of 250MHz routable for (K3 – K5, K7-K8) & (K9 – K13) channels
10 : 8
5:4
Sub-Channel Switch (5:4)
10

DAT Major Components

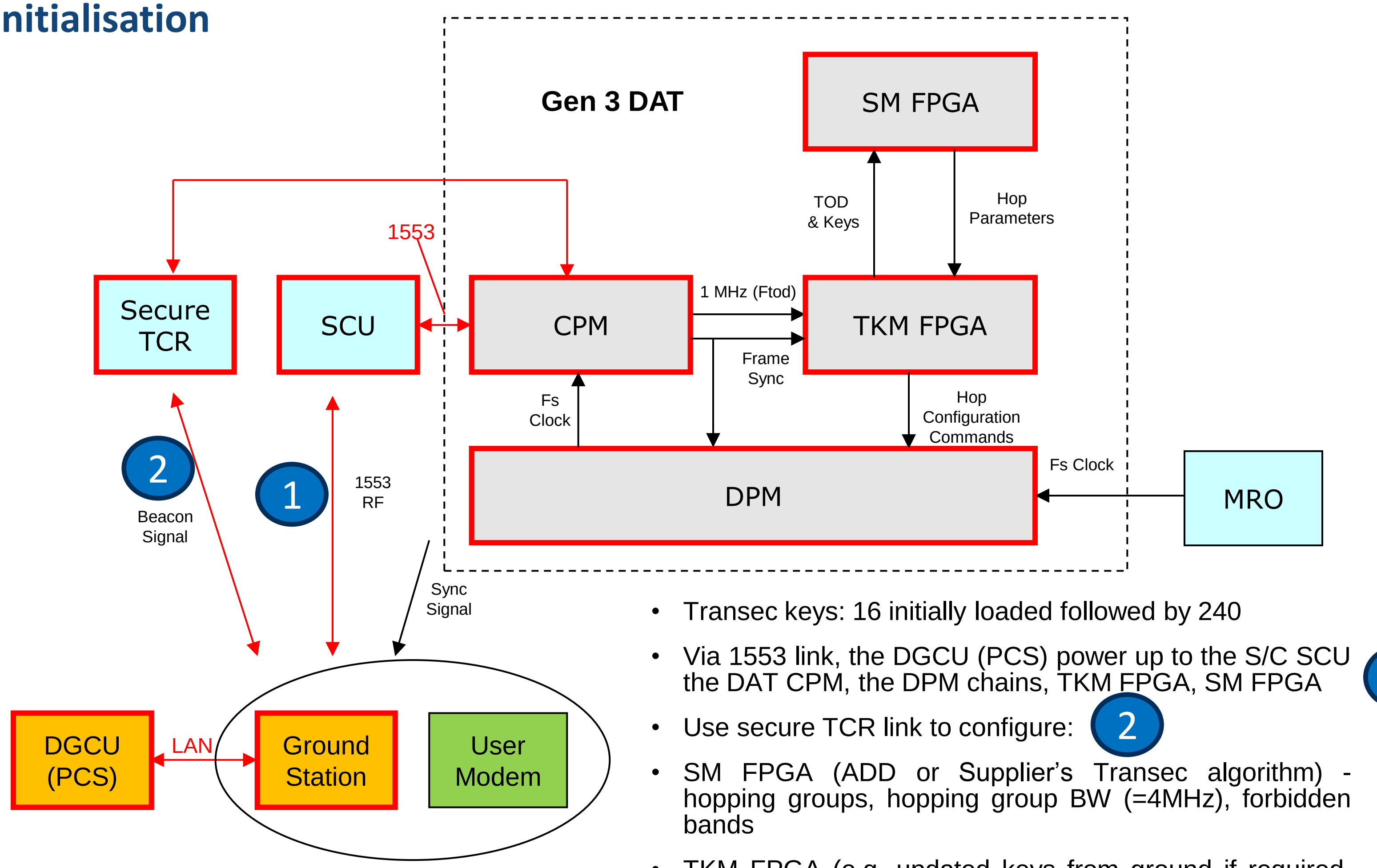


- DPM with processing chains, each has ADC/Demux/Dehop-Rehop Switch/Mux/DAC for dehopping & rehopping the DAT channel signal
- CPM with 1553 interface
- Transec Key Manager (TKM), responsible for generating the time of day (TOD), requesting and distributing TRANSEC keystream data
- Transec (SM) FPGA contains the algorithms for TRANSEC generation
- **Transec algorithm to be provided by supplier**

DAT Functions Overview

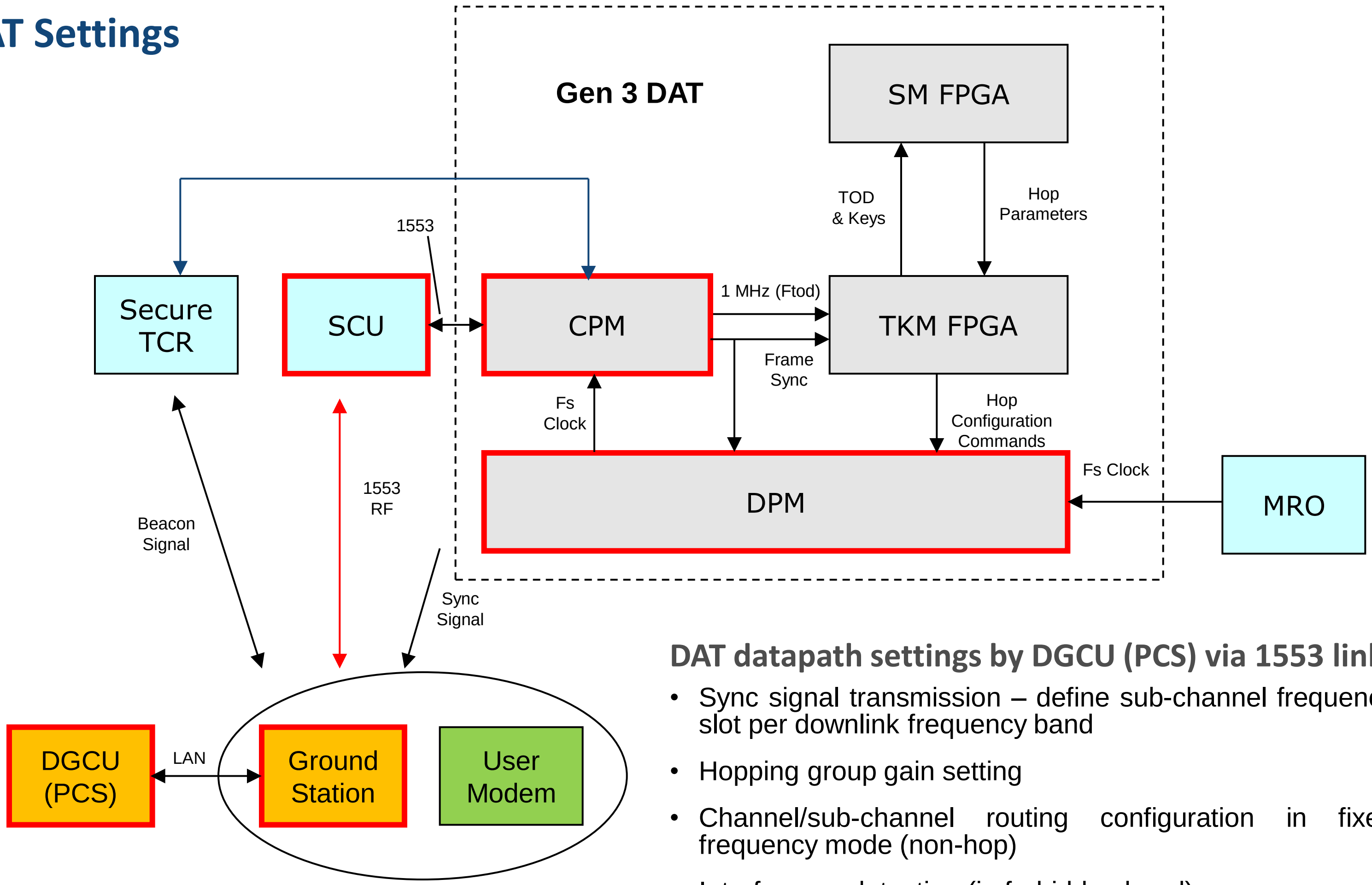
- Ground network allocates users to one of the hopping groups (up to 45 groups of 4MHz each are specified)
- Hopping groups frequency hop within the hopping band
- DAT DSP demux the whole hopping band into granular sub-channels (250 kHz)
- Spectrum analyse hopping band & suppress interferer(s) – 250kHz resolution
- Hopping group is de-hopped & re-hopped as a group of granular sub-channels (e.g. 16 for 4MHz).
- DAT uses different keystreams for the uplink and downlink hopping sequences
  - Hopping group input centre frequency
  - Offset from centre frequency of the group
  - Output centre frequency
- Ground network sets group bandwidth, offsets and forbidden band data, the keys required to generate the input and output TRANSEC centre frequencies

DAT Initialisation



- Transec keys: 16 initially loaded followed by 240
- Via 1553 link, the DGCU (PCS) power up to the S/C SCU the DAT CPM, the DPM chains, TKM FPGA, SM FPGA 1
- Use secure TCR link to configure: 2
- SM FPGA (ADD or Supplier's Transec algorithm) - hopping groups, hopping group BW (=4MHz), forbidden bands
- TKM FPGA (e.g. updated keys from ground if required, set hop period (= 80 µsec & the initial TOD value, key selection).
- It is assumed that the secure TCR command/telemetry data is routed to/from the DSP CPM via the SCU 1553 interface (1kbps rate)

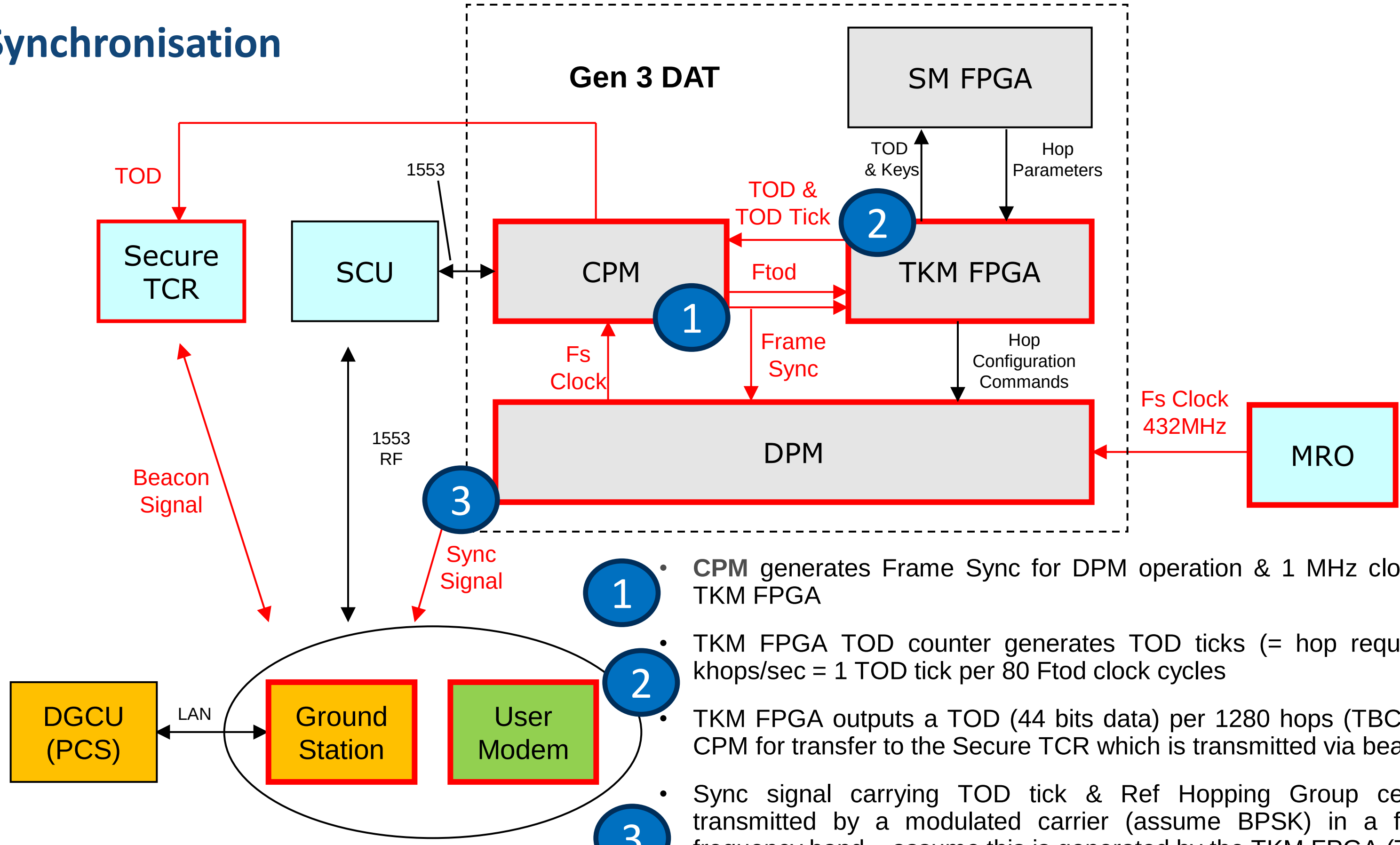
DAT Settings



DAT datapath settings by DGCU (PCS) via 1553 link

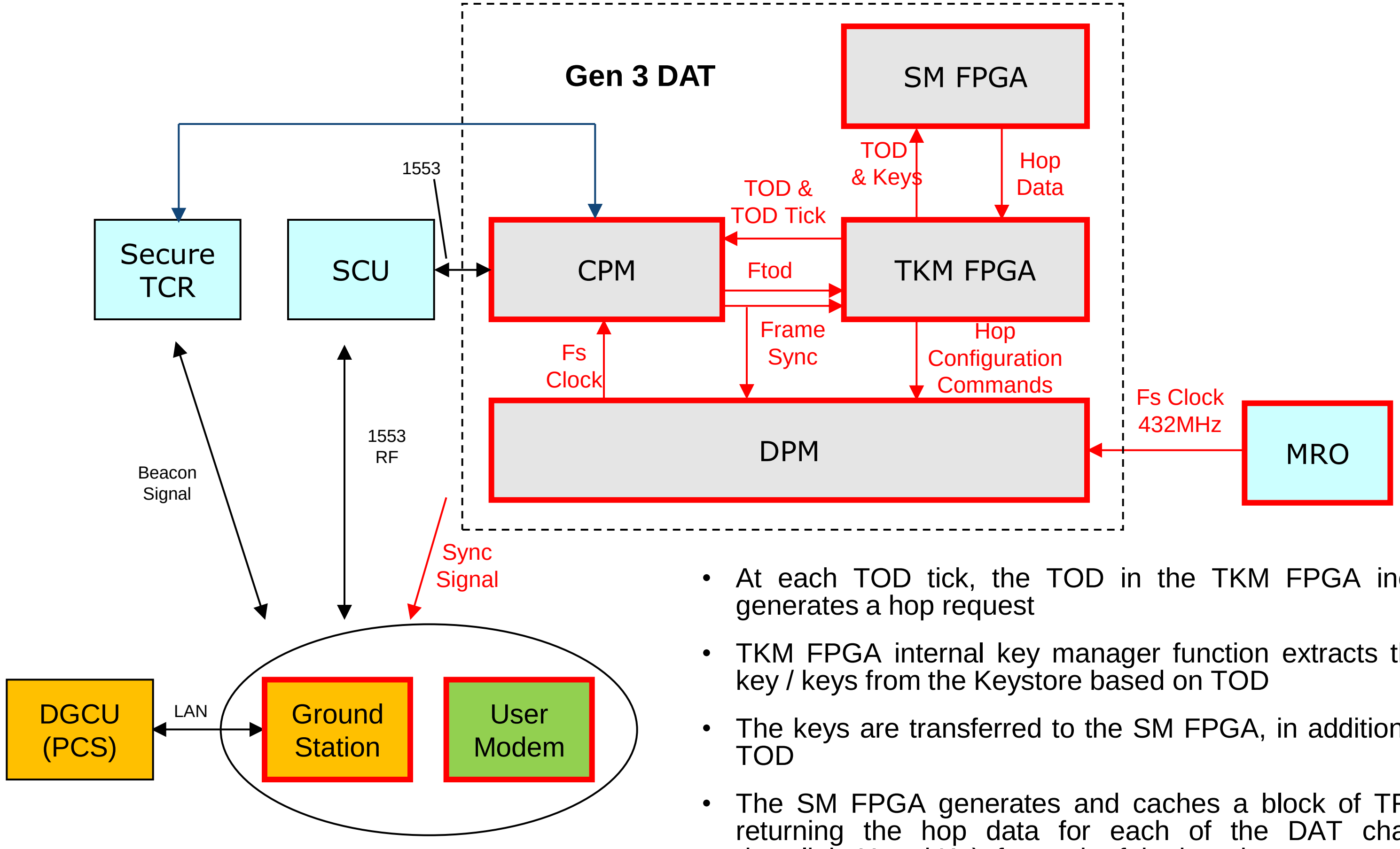
- Sync signal transmission – define sub-channel frequency slot per downlink frequency band
- Hopping group gain setting
- Channel/sub-channel routing configuration in fixed frequency mode (non-hop)
- Interference detection (in forbidden band)
- Interference cancellation

DAT Synchronisation



- 1 **CPM** generates Frame Sync for DPM operation & 1 MHz clock (Ftod) for TKM FPGA
- 2 TKM FPGA TOD counter generates TOD ticks (= hop request) ➔ 12.5 khops/sec = 1 TOD tick per 80 Ftod clock cycles
- TKM FPGA outputs a TOD (44 bits data) per 1280 hops (TBC) to the DAT CPM for transfer to the Secure TCR which is transmitted via beacon
- 3 Sync signal carrying TOD tick & Ref Hopping Group centre freq is transmitted by a modulated carrier (assume BPSK) in a freq slot per frequency band – assume this is generated by the TKM FPGA (TBC)
- User modem in conjunction with the Ground Station use the TOD tick & TOD to align its hop timing, generate the transmit & receive hopping sequence based on the appropriate keys.
- The keys used by the DAT TKM FPGA can be synchronised with ground modem by a time tagged command (the assigned TOD and key select) to the DAT TKM FPGA via secure TCR

DAT Hop Sequence Generation



- At each TOD tick, the TOD in the TKM FPGA increments, and generates a hop request
- TKM FPGA internal key manager function extracts the appropriate key / keys from the Keystore based on TOD
- The keys are transferred to the SM FPGA, in addition to the current TOD
- The SM FPGA generates and caches a block of TRANSEC data, returning the hop data for each of the DAT channels (uplink, downlink, X and Ka), for each of the hopping groups.
- The hop data retrieved from the SM FPGA is routed to the appropriate dehop/rehop switch FPGAs
- The TKM FPGA waits for the next TOD tick

Frequency hopping : On board Hop / De-Hop

- Hop / Dehop is a very robust system for antijamming
  - Need to know the TRANSEC code to jam the payload
  - Implementation is quite simple. Perfect to protect a wide area

- Not efficient in term of capacity
  - The ratio between installed and used capacity is linked to the jammer rejection capability of the system
  - Reducing this ratio will increase the capacity but will reduce the robustness

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Regenerative

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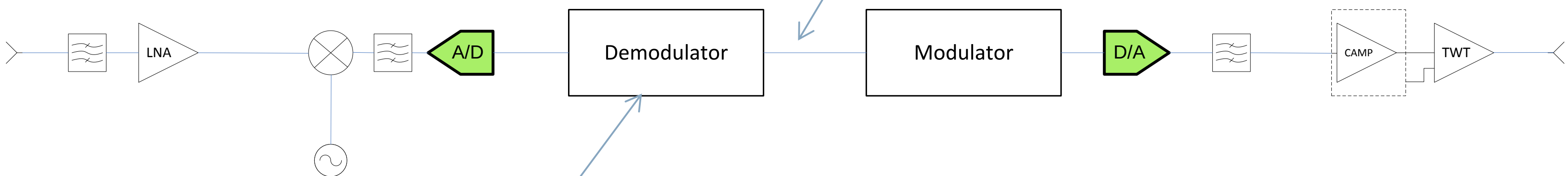
Regenerative

- Regenerative systems are very demanding in term of on-board computing
  - Nearly no commercial satellite regenerative system exists
- They are going to be more popular in the future thanks to the improvement of digital processors
- Regenerative system does on board demodulation and modulation
- If an interference occurs, the useful carrier will be broken and won’t be routed
  - Protection of the output section

Regenerative Block Diagram

Can add routing algorithm in between Filtering at Network Layer 2 or 3



Non recognised waveforms will be eliminated

Very difficult to jam. Need smart jamming (same waveform and packet format)

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Active antenna

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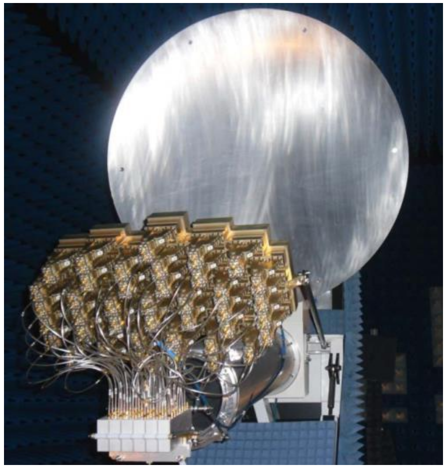
Active antennas - types

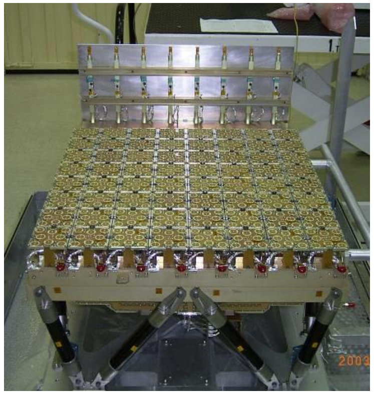
- There is large variety of active antennas
  - With or without reflector
  - With analogue or digital beam forming
  - With anti interferences capabilities

Inmarsat 4

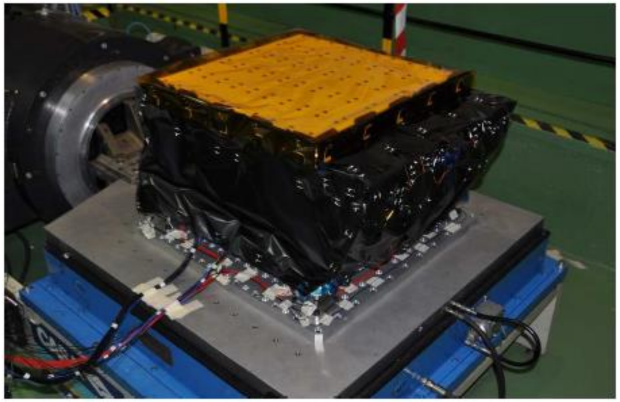
L band AFR with reflector



Ku IPA with reflector



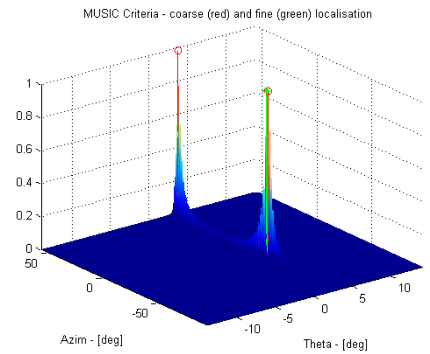
X band DRA



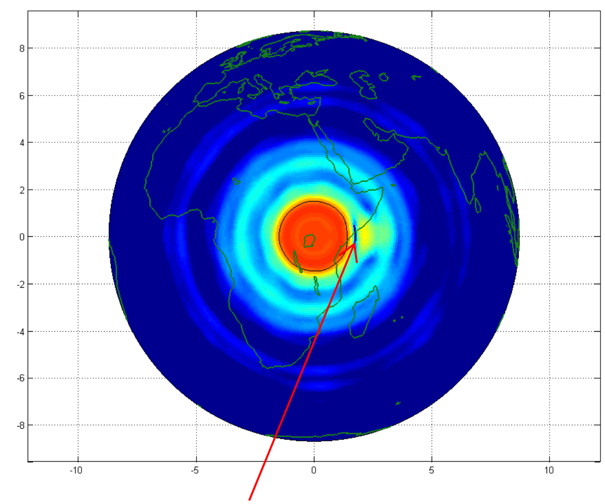
Ku band DRA

Active antennas - purpose

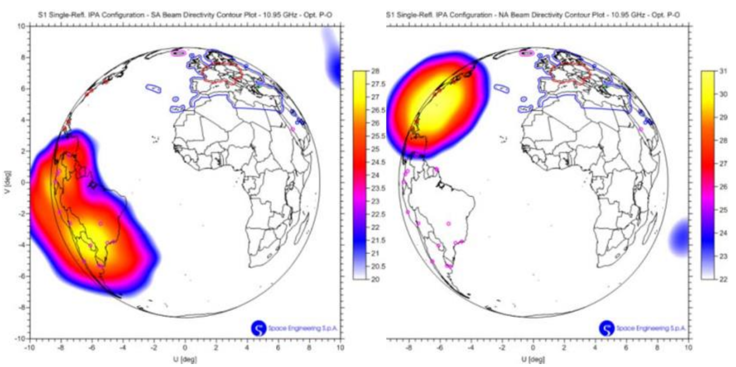
- The purpose of active antennas will be to
  - Create flexible coverages (location / size)
  - To have one antenna system to create several coverages
    - Up to thousands of beams in digital beam forming
  - To create null in the coverages to be protected from a specific location
  - On board High resolution geolocation



High Res Geolocation

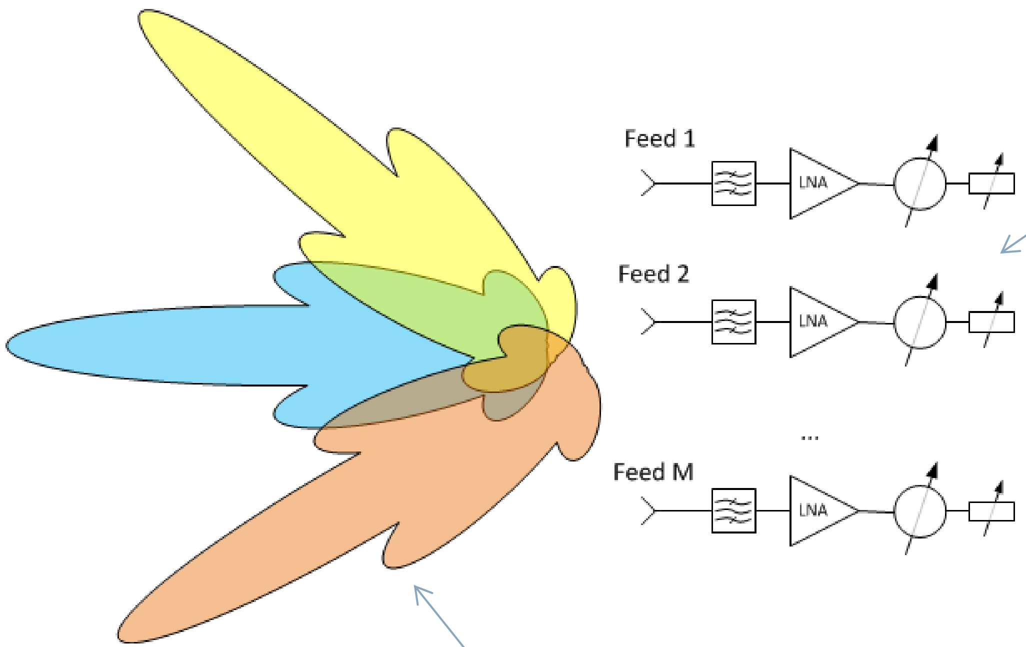


Nulling



Flexible coverages

Active antenna principe



Playing with the amplitude and phase will modify :

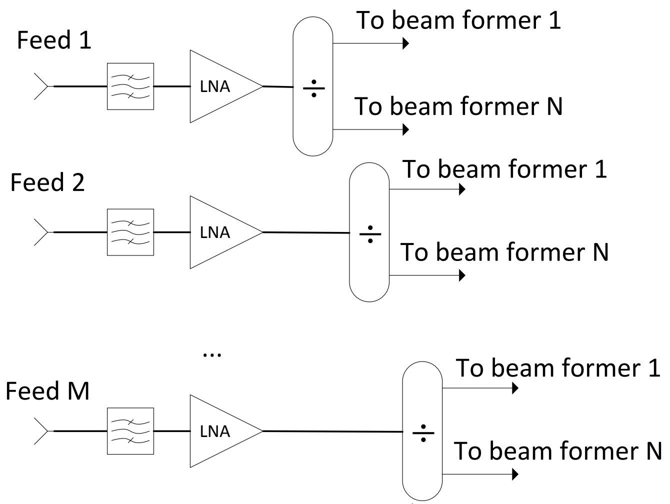
- The beam position : phase slope between feeds
- The beam size : Overall amplitude taper

Large amount of possible beams

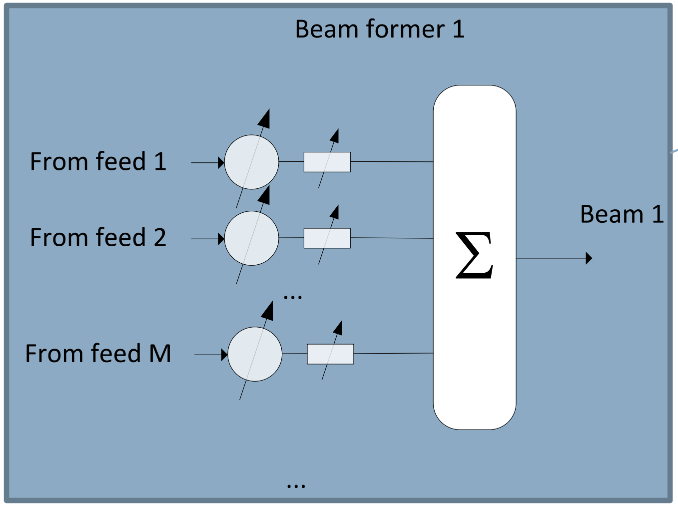
Hardware implementation and constraints

Analogue beam former

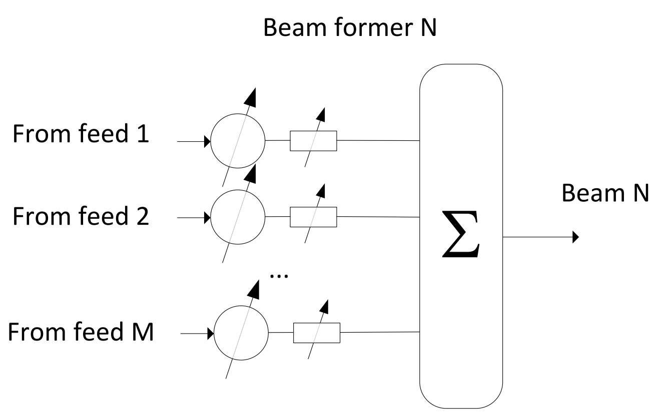
Typically :
Up to 250 feeds



Need length matching between paths



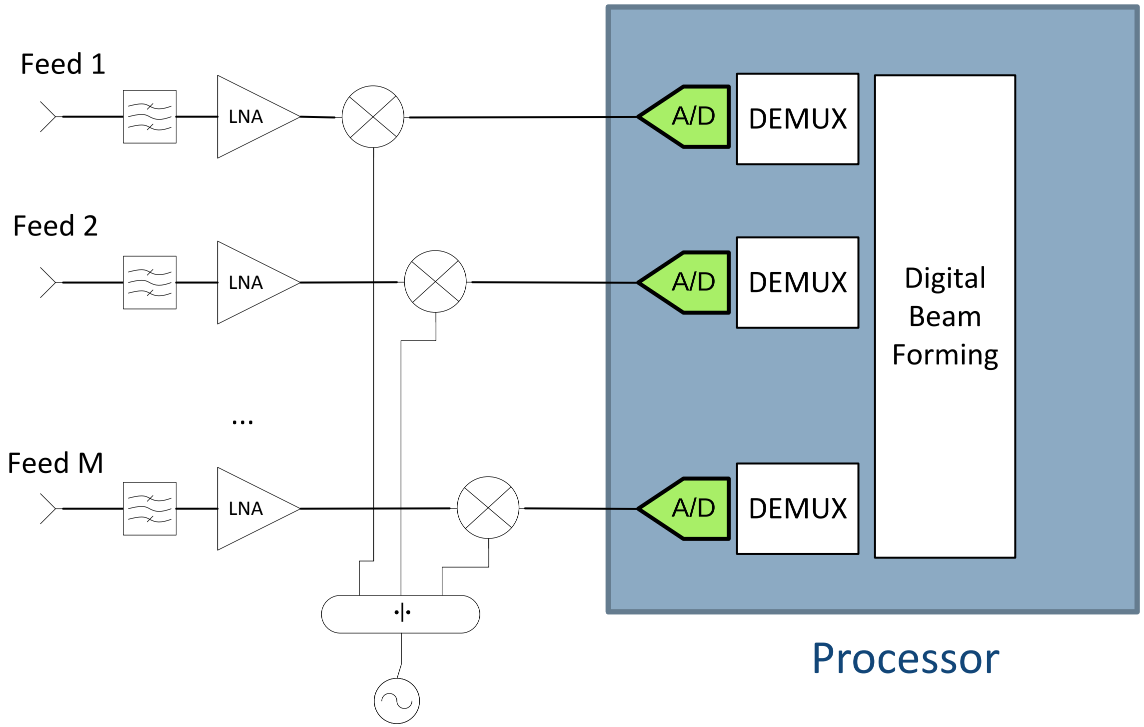
One per beam



Typically :
Up to 16 beams

Hardware implementation and constraints

Digital beam former

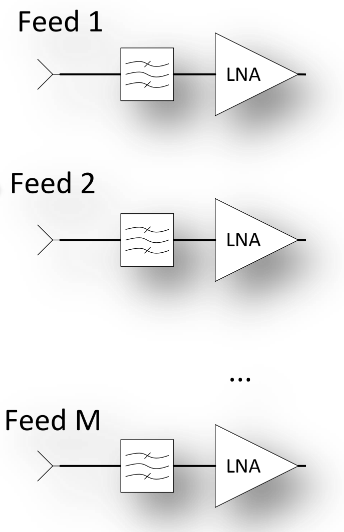


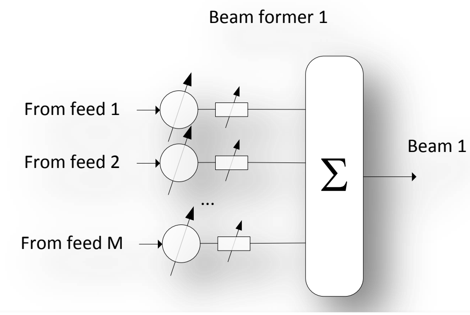
Conversion to IF need to be synchronised

Advantage in antijamming compare to classical antenna

Feed pattern is a wide pattern
Low directivity compared to a directive antenna gain
The gain is 10 log (M) below a typical antenna gain

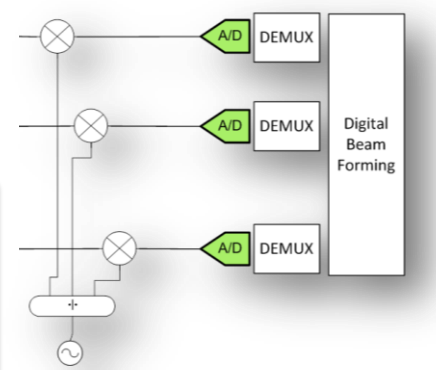
Even more difficult to saturate the LNA





BFN gain recreate the jammer at the same level unless we apply nulling coefficients

ANALOGUE DESIGN



FULLY DIGITAL DESIGN

Mixers and ADC see less power for same reasons
→ **better protection**

Geolocation : High Resolution methods

- Very common methods for feed arrays
- Based on the following assumptions:
  - Number of signals to detect is smaller than the number of sensors
  - Geometry of the antenna is well known
    - This geometry can vary with thermal effects : will impact the performance
  - All the signals are uncorrelated
  - The thermal noise is not correlated with the other signals
- The covariance matrix from the signals coming from the feeds is calculated

High Resolution methods - MUSIC

- MUSIC for Multiple Signal Classification
- MUSIC is probably the most common method for high resolution geolocation

- The covariance matrix can be expressed like that :

$$\hat{R} = \sum_{i=1}^{N_i} \vec{a}(\theta_i, \phi_i) \cdot \vec{a}^H(\theta_i, \phi_i) \cdot P_{s_i} + \sigma^2 \cdot I_N$$

Signals Thermal noise

Can be written like that : $\hat{R} = A \cdot P_s \cdot A^H + \sigma^2 \cdot I_N = R_{ss} + \sigma^2 \cdot I_N$

Signals Thermal noise

MUSIC

- The MUSIC algorithm will use some properties of the covariance matrix
  - Eigenvalues of the covariance matrix are positive
  - We can write the matrix like that :

$$\hat{R} = \sum_{n=1}^{N} \lambda_n \vec{u}_n \cdot \vec{u}_n^H$$

  - And this matrix can be divided into two sub spaces :

$$\hat{R} = \sum_{n=1}^{N_i} \left(\mu_n + \sigma^2\right) \cdot \vec{q}_n \cdot \vec{q}_n^H + \sigma^2 \sum_{n=N_i+1}^{N} \vec{q}_n \cdot \vec{q}_n^H$$

Highest eigen values = signals

Lowest eigen values = noise

MUSIC

- As the signals and the thermal noise are uncorrelated, the two sub spaces are orthogonals
- The sub spaced linked to the thermal noise is orthogonals to the direction vectors of the signals
- The MUSIC algorithm is done in several steps :
  1. Estimation of the covariance matrix
  2. Calculation of the eigenvalues and eigenvectors
  3. Estimation of the thermal noise sub space
  4. Projection of direction of arrivals on this sub space

Highest eigen values = signals

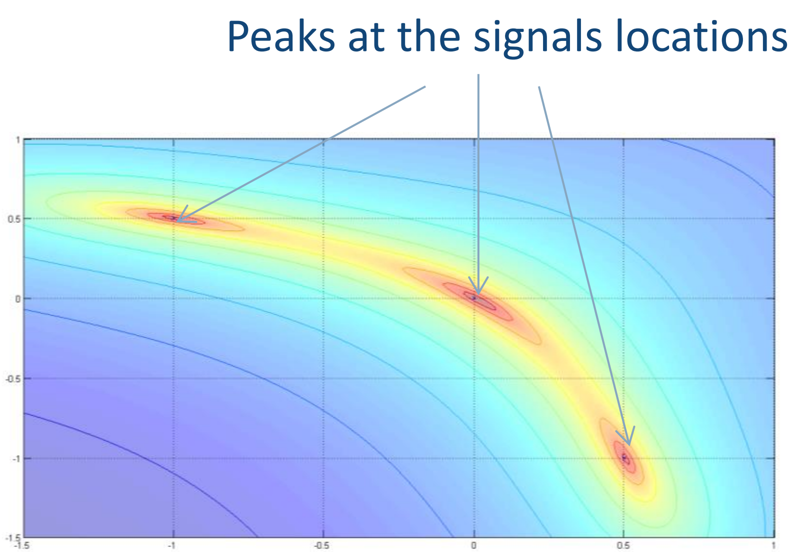
Lowest eigen values = noise

GEOLOC MUSIC

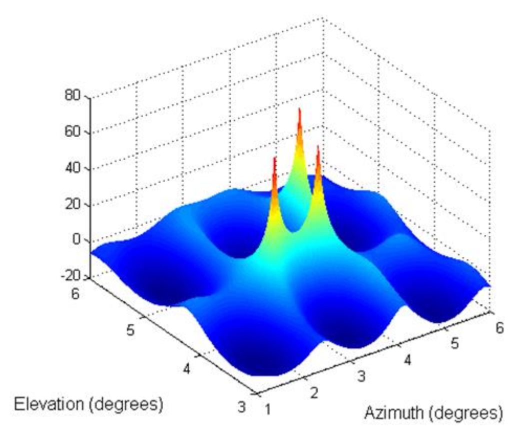
- Provides very accurates results
- Accuracy is roughly 1/10 of the minimum beam size
- Number of simultaneous signals (at the same frequency) limited by the number of sensors

Accuracy limited by:

- Geometrical uncertainties of the sensors position (manufacturing + thermal)
- RF mismatches generating phase estimation error



Examples of results



GEOLOC MUSIC – System implementation

Satellite

- Calculate the covariance matrix
- Send the result to the ground by telemetries
- Advantage of the covariance : the measurement done on a high number of samples is synthetize in a NxN matrix where N is the number of sensors. It plays also a role of data compression which is essential for the tonicity of the service

Ground

- Apply the geoloc algorithm
  - Not done on-board (in 95% of the cases) because the algorithm is quite heavy to implement. It's also possible to improve it (smooth MUSIC…) and some improvements can depend of the configuration
- Can potentially calculate the new beam weights (in active antenna case for the mission) to null the jammer

GEOLOC MUSIC – Hardware implementation

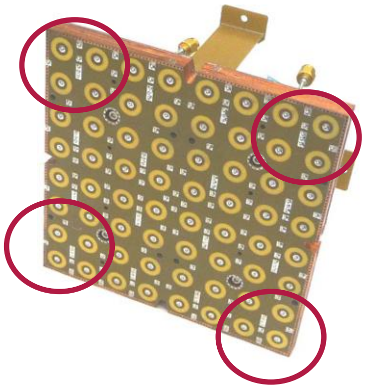
Analogue to digital conversion is required to make the correlation
But geoloc high resolution system are not necessarily done with processor for the payload mission

Analogue BFN

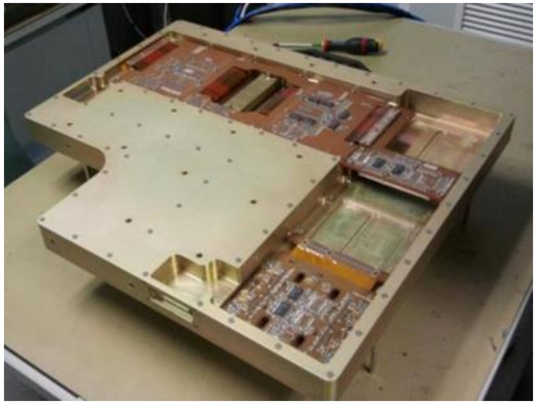
- Dedicated processor
- Only some feeds are equipped with some ADC
- Can be dedicated narrow band ADC and flexible frequency converters to sweep over the spectrum

Digital BFN

- Straight forward : Calculation done on the payload signal within the DSP



8x8 Ku band DRA
Analogue BFN
Only the extremum feeds are equipped to get the better accuracy



Control unit

High resolution Geolocation – Other methods

MUSIC algorithm can be difficult to implement on-board as it require eigen vector extraction and a long process of vector projection

Other high resolution methods exists with lower performances or some hardware constraint but with easier implementation on these complex computation aspects

CAPON

- Minimization of the received power of the incoming signal in all direction by maintaining a unity signal in the look direction
- Peak are obtained by vector projection on the inverse of the sample correlation matrix

$$P_{Capon} = \frac{1}{\left[\vec{a}(\varphi)\left[\vec{R}_{xx}^{-1}\right]^H \vec{a}^H(\varphi)\right]^H} = \frac{1}{\vec{a}^H(\varphi)\vec{R}_{xx}^{-1}\vec{a}(\varphi)}$$

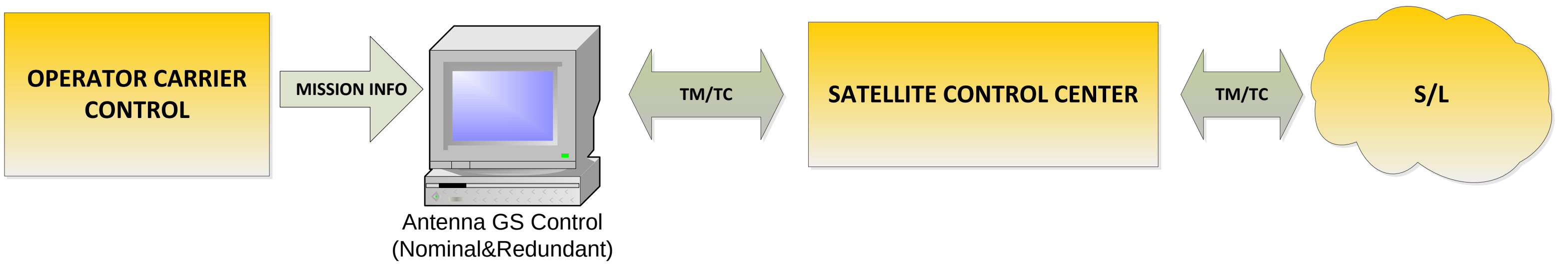
ESPRIT

- Using rotationnal invariance technique : doesn't need the vector projection process
- But requires two times more sensors

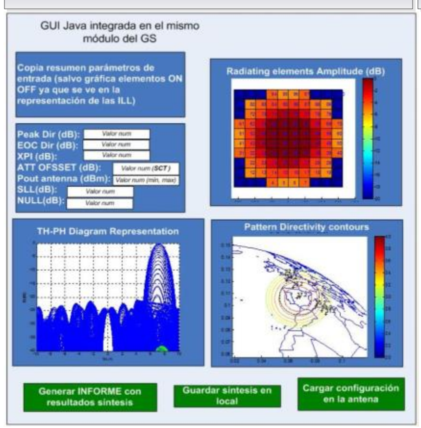
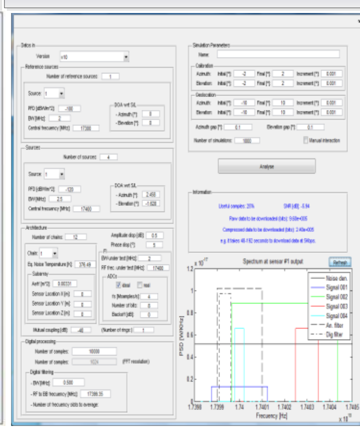
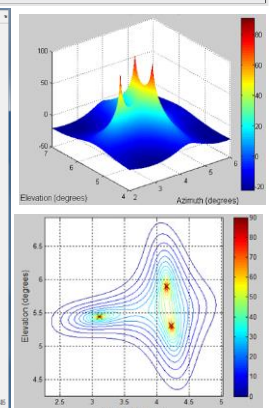
Nulling

- When the jammer has been geolocalize, the complex beam weights that creates the beams can be updated to reduce the gain in the interferer direction
- There are two possibilities
  - **On ground update**
    - More computing power
    - Can assess the impact on the overall system : better control
    - Longer loop : Difficult to correct quick thermal and platform effect
    - Limited also by the knowledge of the hardware performances : aging, phase mismatch is difficult to take into account, and calibration is never perfect
  - **On board update – Adaptive nulling**
    - Simple on-board algorithm
    - Need to be robust to avoid divergence : This is a very difficult aspect !
    - Very fast : can take quick effect into account
    - Done directly in the payload referential : can remove by nature some RF mismatch
    - Can potentially provide the best nulling performances

Nulling – On ground update



GROUND CONTROL for ANTENNA SYSTEM

GUI for BEAM PATTERN SYNTHESIS	GUI for GEOLOCATION MODULE
	 

Nulling – On board implementation of adaptive algorithm

- Need a Robust and simple to implement method of beam forming for nulling

MVDR

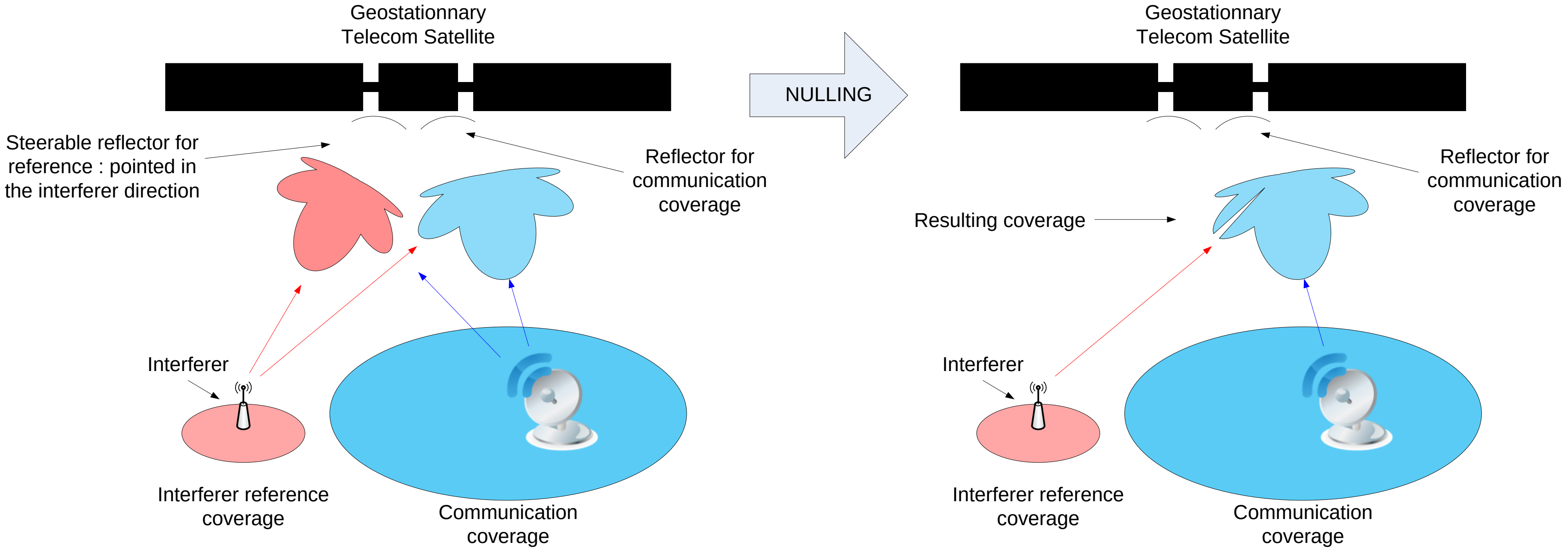
- Minimum Variance Distortion less Response (MVDR) – called also the CAPON beam former
- Minimize the variance / power of the interference
- Make assumptions on the useful signals : can diverge if the useful signal doesn't have the good characteristics during measurement → misinterpretation of who is the good or bad signal !

General sidelobe cancellation

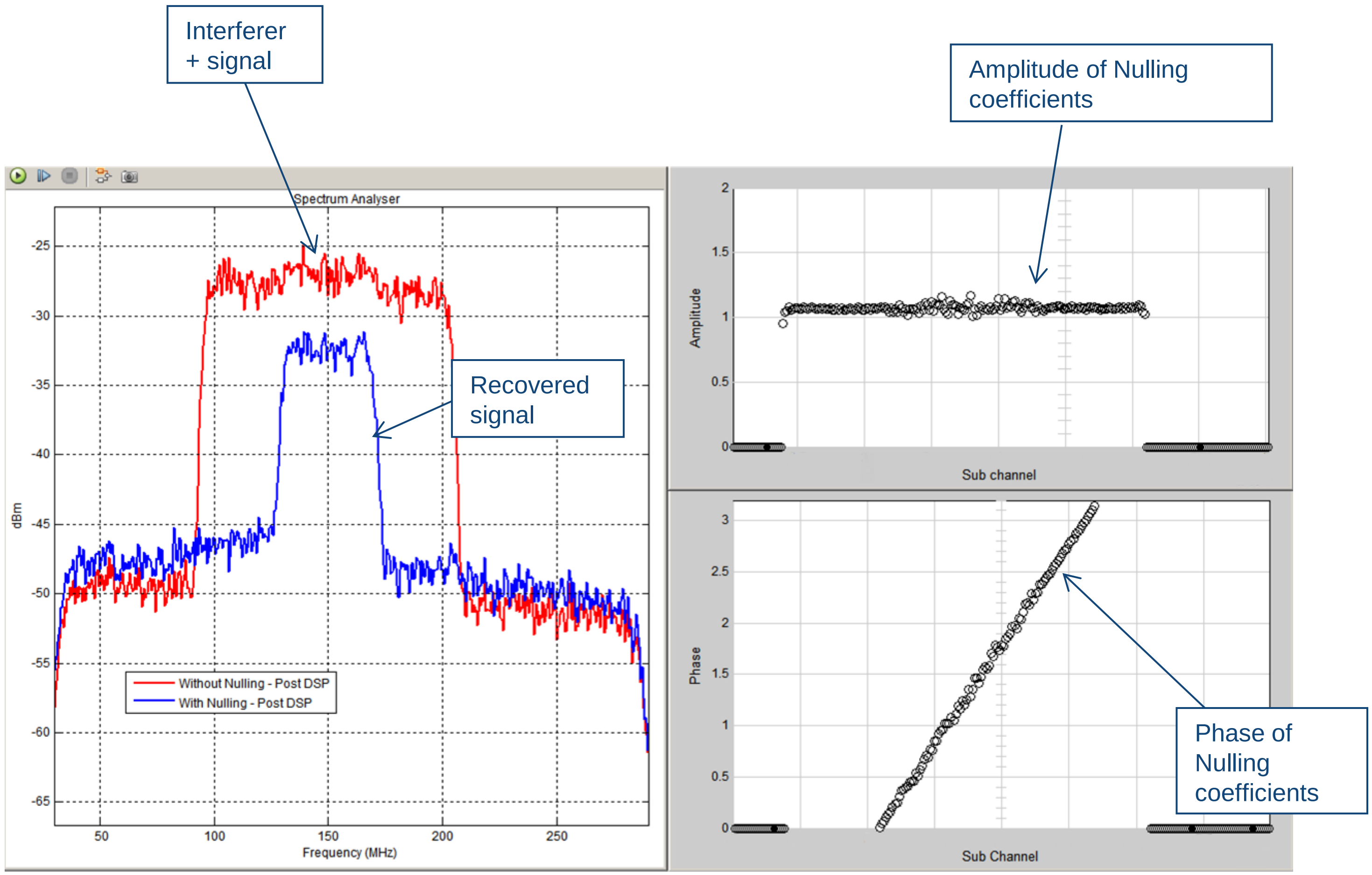
- Create a beam in the direction of the jammer
- Sum this beam in phase opposition to the main beam
- Better control compared to MVDR
- Can be implemented with steerable antennas

general side lobe cancellation

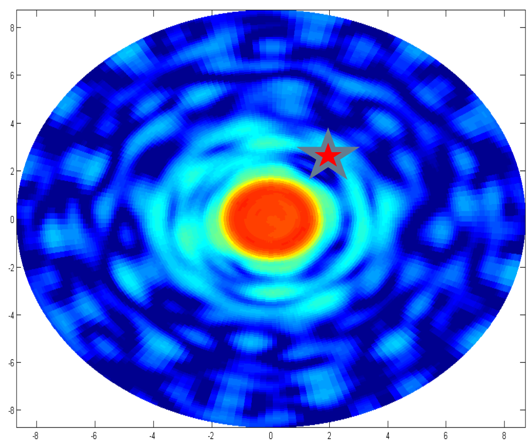
- A « reference » beam is pointed in the direction of the interferer
- And is substracted from the main coverage (with the good complex weighting) to null the interferer

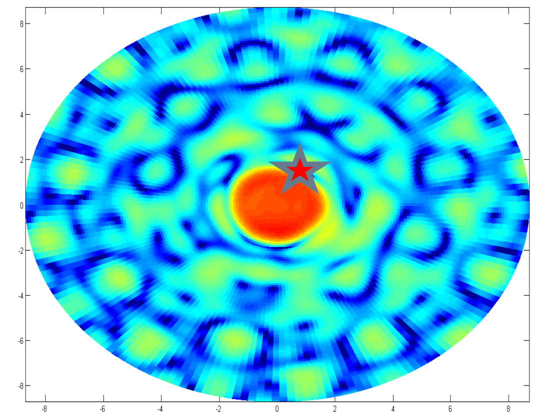


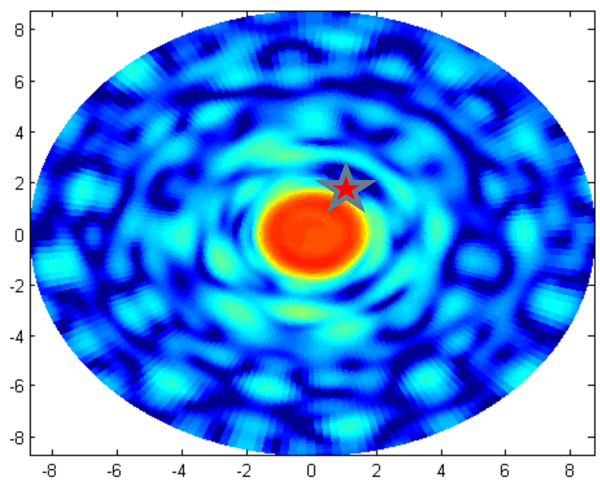
Example of signal recovery



Example of signal resulting coverages with general side lobe cancellation







The nearest the jammer, the worst the performance on the useful coverage

Degradation of the useful gain and increase of the thermal noise (by complex addition between noise of the useful beam and noise of the reference beam)

Conclusion on active antenna

- Active antenna is a powerful system for antijamming
  - Very good geolocation system
  - Geographic nulling
    - Mission with traditional modems can be protected
  - Quite robust
    - Robust by design at LNA level : better protection versus very powerful jammers
    - Nulling algorithms provide a good protection versus jamming… but require watchdog systems to avoid divergence
- Use of active antenna and frequency hopping (at modem level) is quite common in military system
- Mix with a on-board dehop / rehop system would provide the best performance and the most robust system

Conclusion

- The increase in the payload design complexity from bent pipe to processed payload with dehop / rehop or active antenna has shown that :
  - The resistance to jamming has to be anticipated. A design not done to resist can't be updated during flight to better resist
  - The level and the complexity of the threat that is specified will be a major driver of the final solution
- Processor and active antenna (can be combined) provide the best on-board solution for antijamming in all domain (detection, geoloc and recovery)
- Frequency hopping modem increase the robustness and can be accommodated on transparent transponder
- On board Dehop / Rehop provides the best robustness
- Nulling by active antenna gives the best protection to very high power jamming

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