Satellite radio-frequency payloads and instruments - Overview and challenges

TEC-EFP
RF Payload Engineering and Digital Equipment Section
RF Payloads and Technology Division
Electrical Department, Directorate of Technology, Engineering and Quality
European Space Agency – ESTEC
02/10/2023

Agenda

- 14:00 Satcom tutorial:
  - Overview of satellite Communications Payloads
  - The need for Flexibility
  - Flexible Payload Architectures
  - Enabling Technologies
  - GEO vs non-GEO systems
  - Challenges Ahead
  - Digital processors
  - DBF quantitative scenarios
  - Efficient DBF algorithms
  - Processing Components for next generation
- 16:00 Earth observation tutorial:
  - Intro
  - Radar architectures
  - SAR applications
  - SAR data rates
  - Future SAR missions
  - Digital Backends for radars
  - Cognitive SAR
  - Future SAR on-board processing
  - RFI
- Q/A session

Satellite Communication Payloads: an overview of past, present and future trends and challenges

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Topics – Satellite Communication

- Overview of satellite Communications Payloads
- The need for Flexibility
- Flexible Payload Architectures
- Enabling Technologies
- GEO vs non-GEO systems
- Challenges Ahead
- Digital processors
- DBF quantitative scenarios
- Efficient DBF algorithms
- Processing Components for next generation

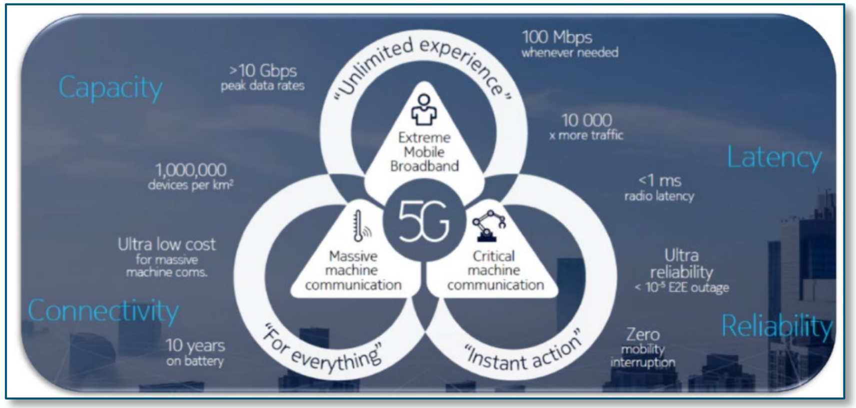
Satellite Communication Applications

Satellite communication classical applications include:

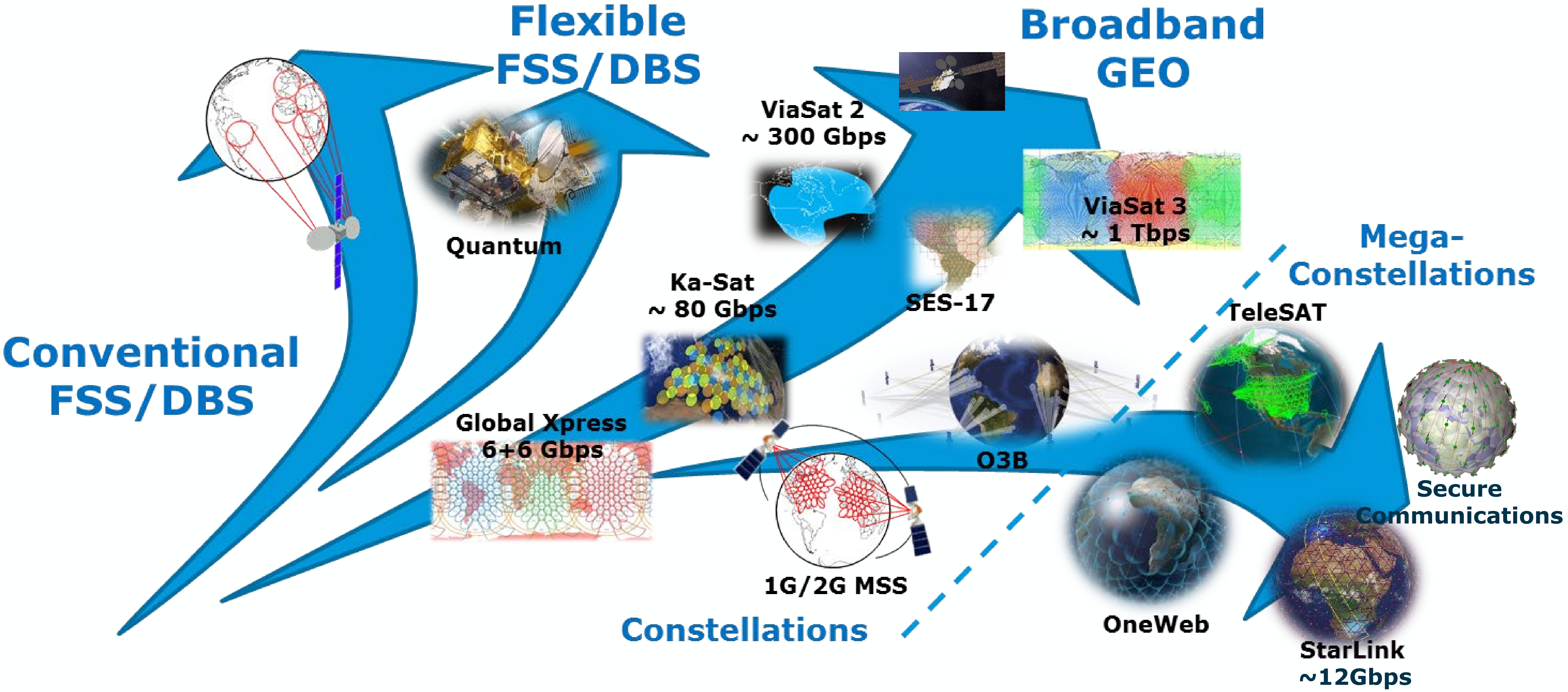
- *Broadcast services*
- *High speed Broadband Services*
- *Mobile connectivity*
- *In flight connectivity*
- *Secure Communications*
- *IoT Services*
- *Requirements on: latency, coverage, availability, high rates, low power*

…and possibility to contribute/extend 5G networks with the 5G NTN component…

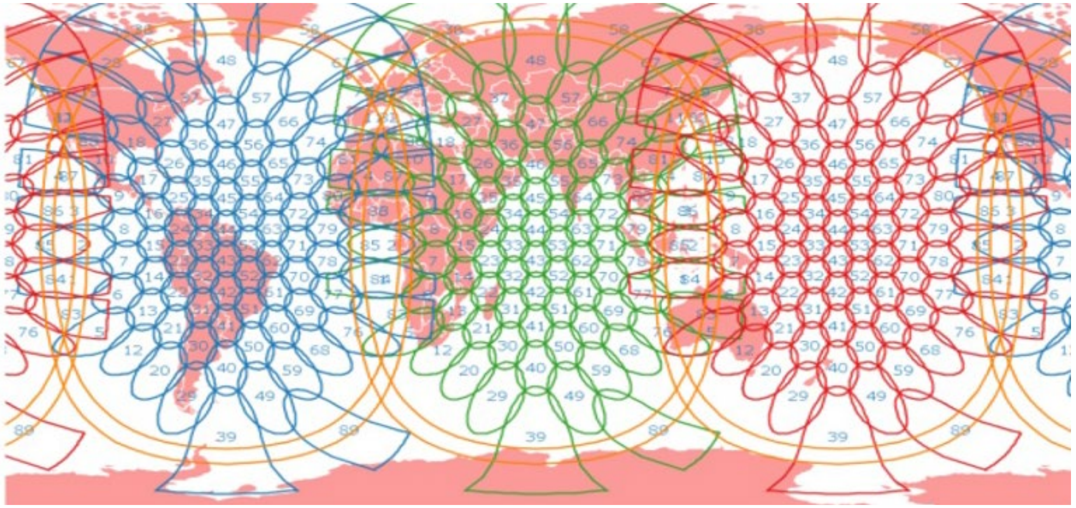
… but many challenges ahead!



Satellite Communication Systems – Trends (Excluding New Space)

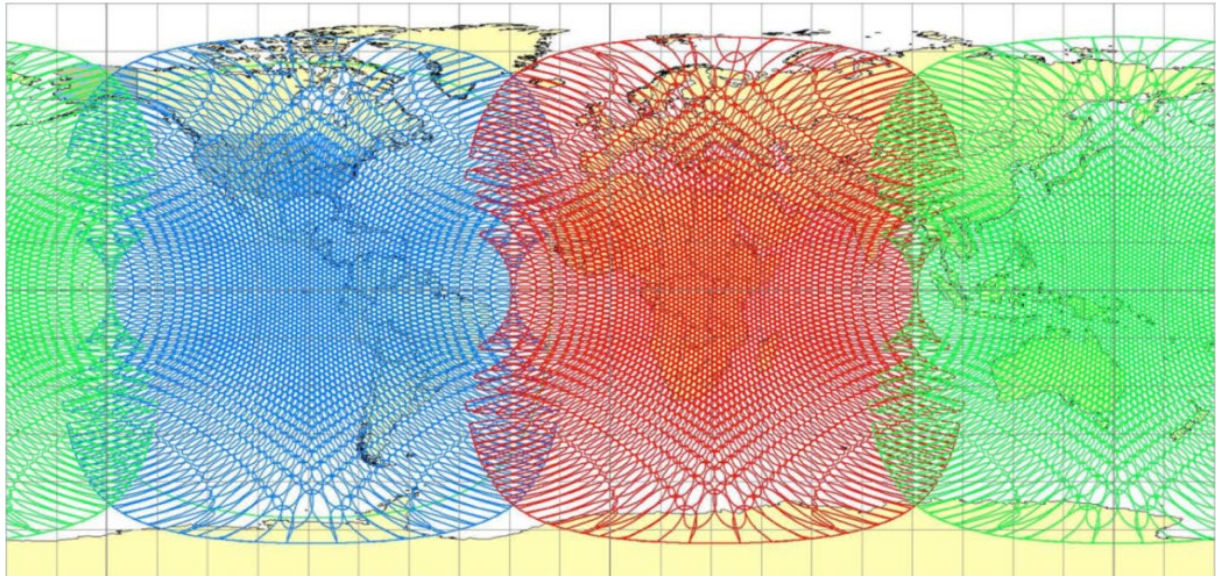


The Challenge until now … Terabit(ps) GEOs



Inmarsat 5

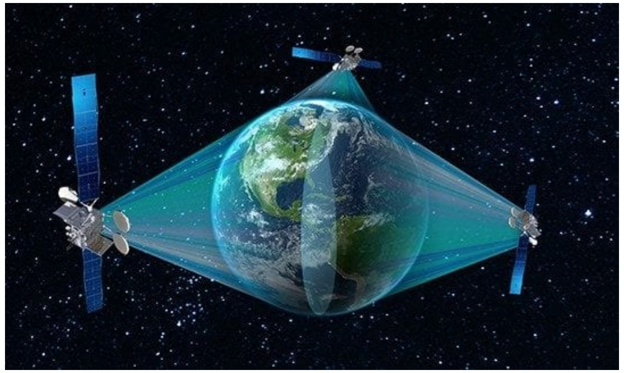
ViaSat 3 (Announced) ~2500 beams per satellite

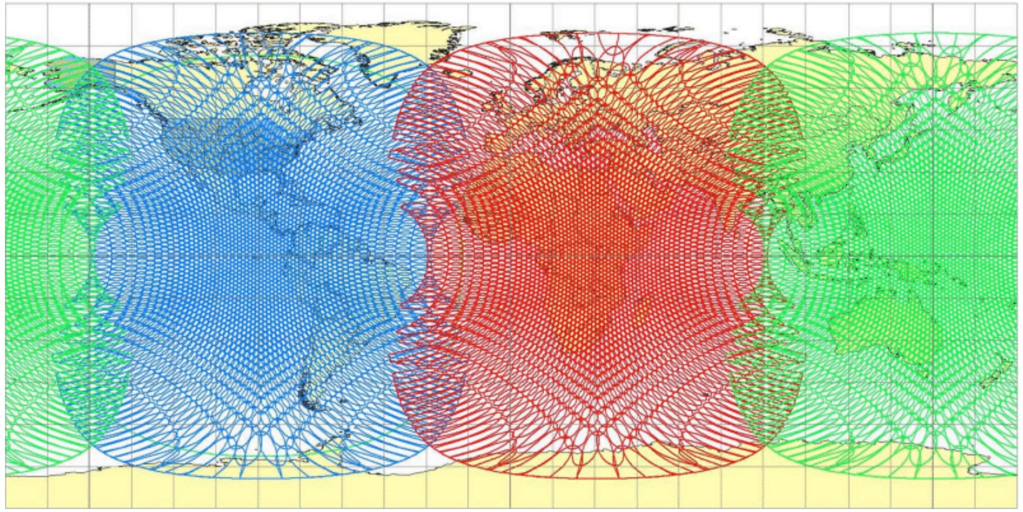


- Trend until approx. 2017-2018 to target VHTS per single GEO satellite (~1Tbps per satellite)
- Targeting maximum capacity is often not able to offer full payload flexibility (e.g. coverage/beamforming flexibility with digital processors)
- Digital beamforming at element level is currently not yet feasible for supporting the full capacity (too high power consumption)

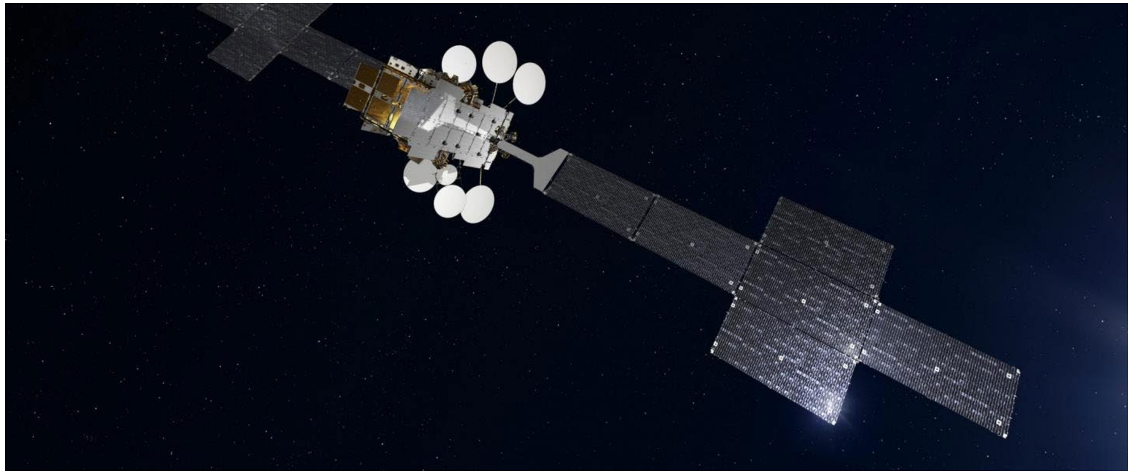
Examples of VHTS systems - Bent-pipe – Single feed per beam

- Viasat-1/2 (VHTS)

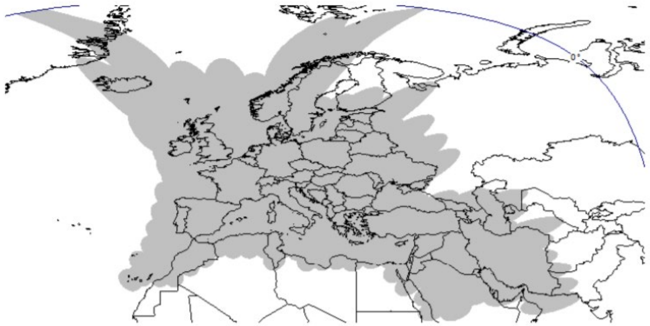




- SES-17 (VHTS)

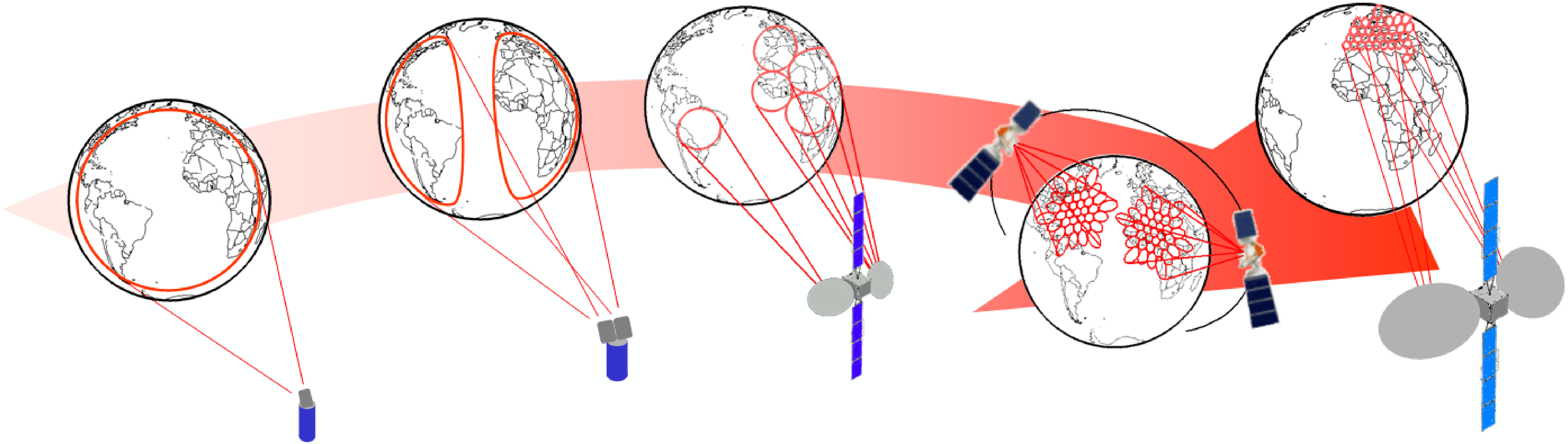


- EUTELSAT KONNECT (VHTS)



SATCOM System Needs for Flexibility

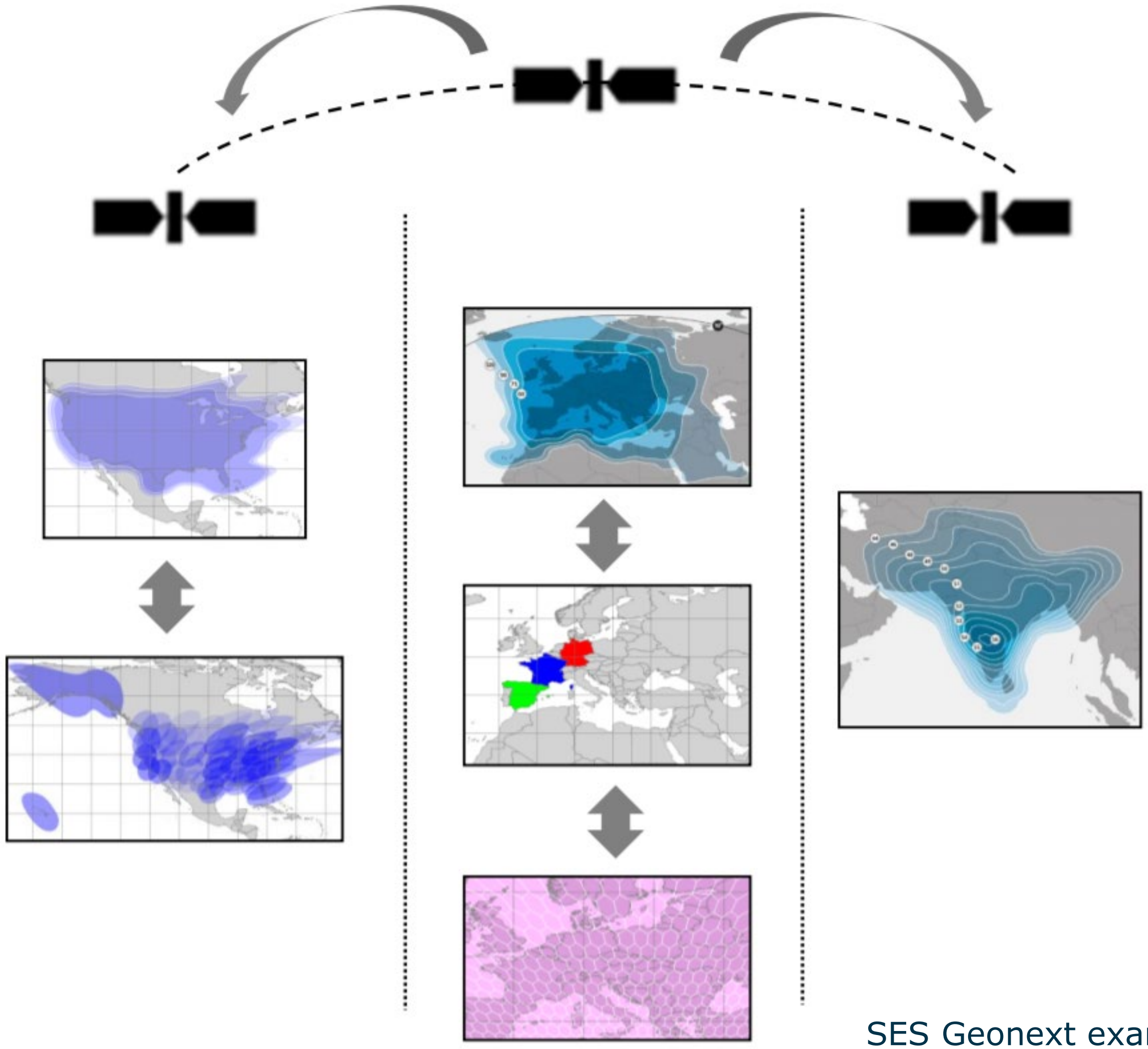
- High degree of coverage and mission re-configurability during lifetime to cope with time variant commercial requirements
- Simultaneous support of multiple beams (global and regional) or large number of spot beams with high level of frequency reuse with in-flight re-configurability
- Increased request for flexibility (coverage, power, signal)



Recent GEO Trend – Flexible Medium Capacity

Since 2017/2018, for GEO the attention has also moved toward the capability to achieve flexible, medium capacity, short time-to-market satellite solutions

- Targeting mainly Ku/Ka-band services on continental coverage for both broadband and TV broadcast
- Throughput Range 50-100Gbps), with beams of moderate size (about 0.5 degs).
- Payloads based on digital processors and array-fed reflectors with about ~100-200 radiating elements.
- Payload Power Consumption expected in the range 10-15kW
- Coverage flexibility is a key requirement (shaped beam and spot beam capability-reconfigurability)



SES Geonext example, *source www.ses.com*

Call for Flexibility

Operators' Expectation

- Flexibility to adapt to evolving business conditions
  - Market evolution (services and/or users)
  - Satellite Operator Competition
  - Terrestrial Network Competition
  - Evolution of Terminal Technology (Transparency)
- Early entry into new markets
- Rationalization of the procurement process (schedule, less customization)
- Efficient operations (Payload Resources, in-orbit redundancy, different orbital slots)

Manufactures' Expectation

- Increase of generic equipment volumes
  - Less customization
  - Decrease of equipment types
  - Increased production runs, Wider range of usage
  - Effective buying/stocking policy for parts
- Reduced Non Recurring Engineering (NRE)
- Late definition/modification of the missions
- Industrial competitive advantages
  - Differentiator wrt competition
  - At regime lower costs and shorter schedule

KEY TECH

Active Antennas

- Power / coverage / orbit flexibility

On-Board Digital Processors

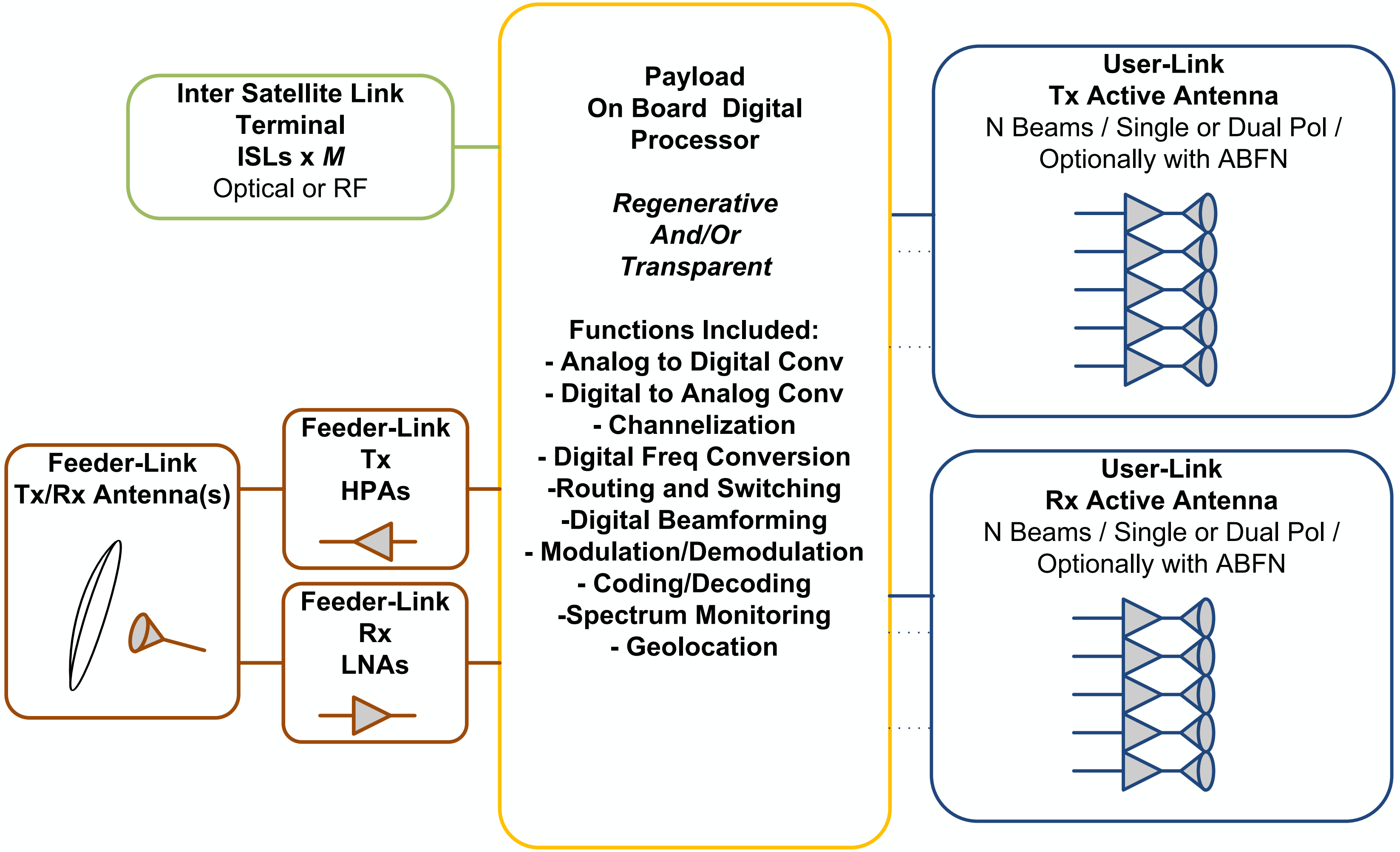
- Routing / switching / beamforming / hopping flexibility

Flexibility, modularity, scalability, genericity

High Throughput and Flexible system – Payload Needs

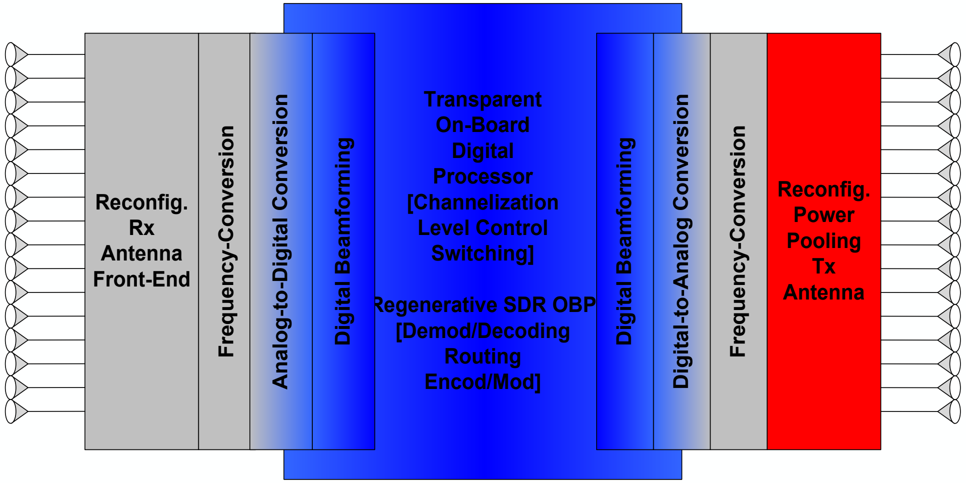
System Needs	Payload Response
Flexible coverage to: adapt to mission requirements, allow reuse in different orbital slot	Active user link Antenna/Payload
Flexible Resource Allocation in time/space to cope with non-uniform traffic needs	Flexible power/beam allocation -> Active Antenna on user-link Flexible BW/beam allocation -> OBP
Flexible Feeder links to support: reconfig. GWs locations, gradual GW deployment	Flexible mapping of GWs into user beams
Larger BW per satellite (both feeder and user links)	Freq reuse on user link and Higher Freq bands for Feeder Link
Flexible Beam Size to cope with non-uniform traffic needs	Active user link Antenna/Payload
Smaller minimum beam size to cope with the need to deliver higher throughput	Adoption of Large Aperture Antennas
Higher beam frequency reuse to provide a higher throughput per satellite	Adoption of Large Aperture Antennas
Reduced production cost and time	Modular/Scalable Payload Architecture with standardized interface
Space segment adaptation to the gradual traffic growth for new markets	Smaller payloads in co-located orbital locations (GEO) with flexible coverage capability

Simplified Satcom Payload Block Diagram

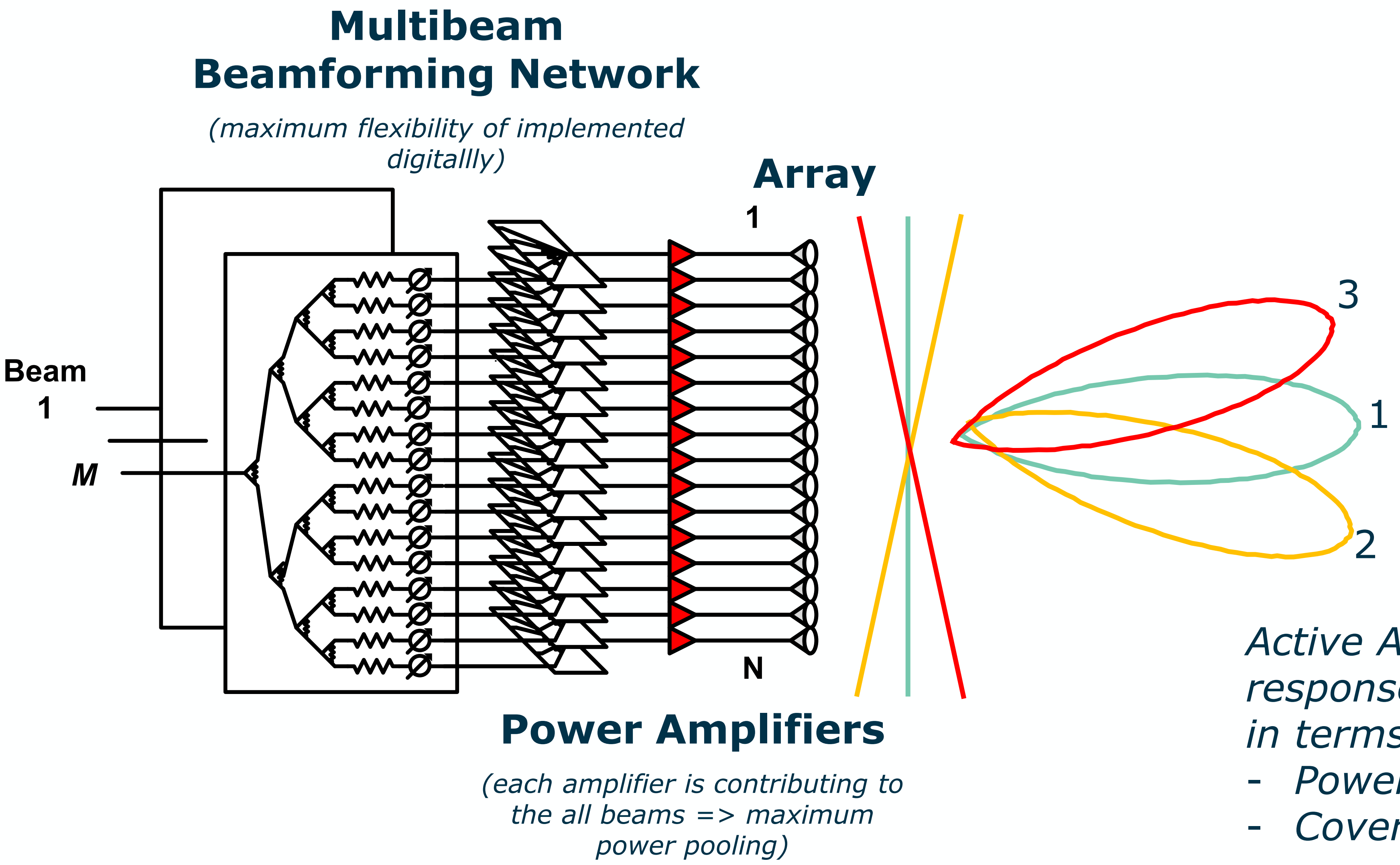


The “Dream” SATCOM Payload

- **Modular (active) antenna** able to cope with different type of missions with flexibility in power allocation
- Compact low-mass/low-power modular **RF Frequency Conversion Chains** (one per antenna feed)
- **Core common digital processor, reprogrammable and reconfigurable** providing the required flexibility in terms of:
  - Satellite coverage
  - Beam shape
  - Beam frequency allocation / Beam Hopping
  - Regenerative Functions: MOD/DEMOD, COD/DECOD
  - Frequency Channelisation
  - Routing and Switching (also to Inter-Satellite Links)
  - Sharing between bent-pipe and meshed capabilities
  - Payload self-calibration
  - Geolocation and Spectrum Monitoring Functions
  - Future “ready” (e.g. 5G compatible)



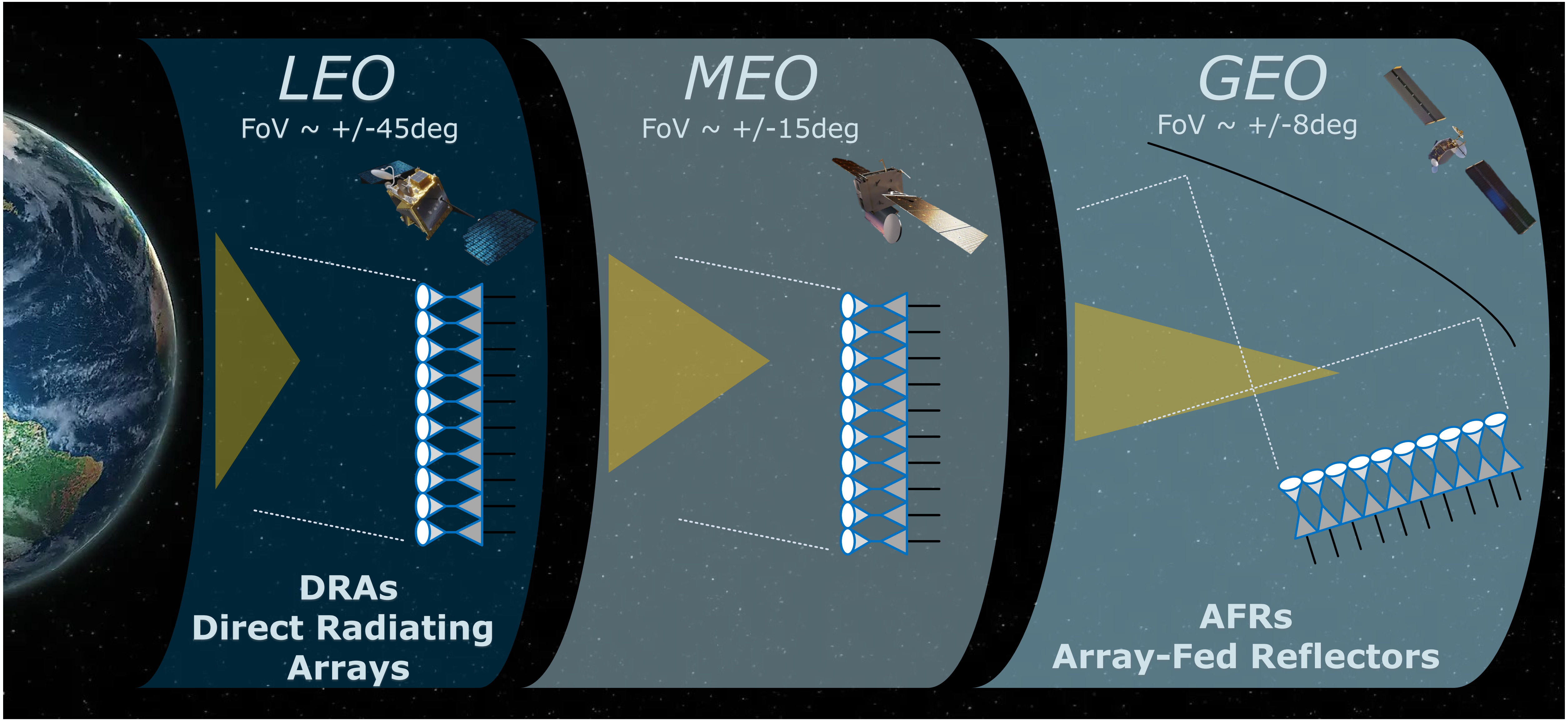
Multibeam Active Array - Principles



Active Antennas are the natural response to the need of flexibility in terms of:

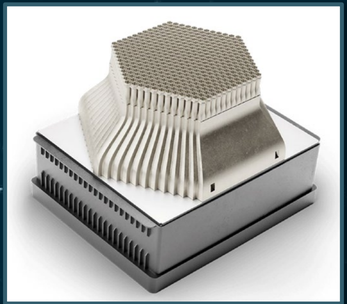
- *Power Pooling*
- *Coverage Reconfigurability*

Active Antennas in LEO, MEO and GEO



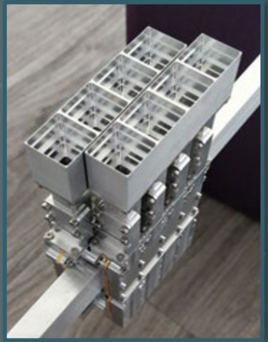
ESA R&D developments on SATCOM Active Antennas

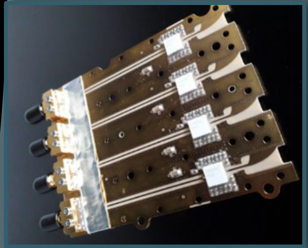
LEO



LEO active antenna demonstrator during antenna test (Courtesy Airbus Defence and Space).

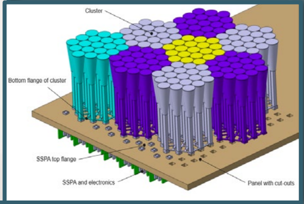
MEO



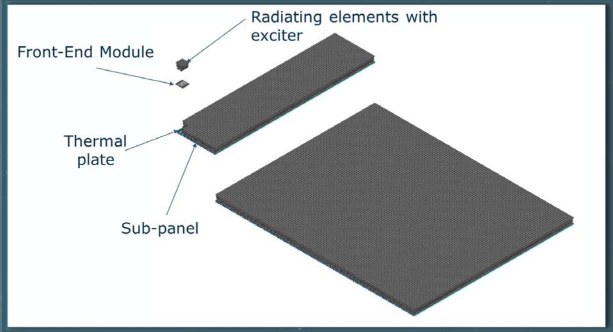


Ka band Front End Radiating Module and HPAs for MEO active antennas (Courtesy of Thales Alenia Space)

GEO

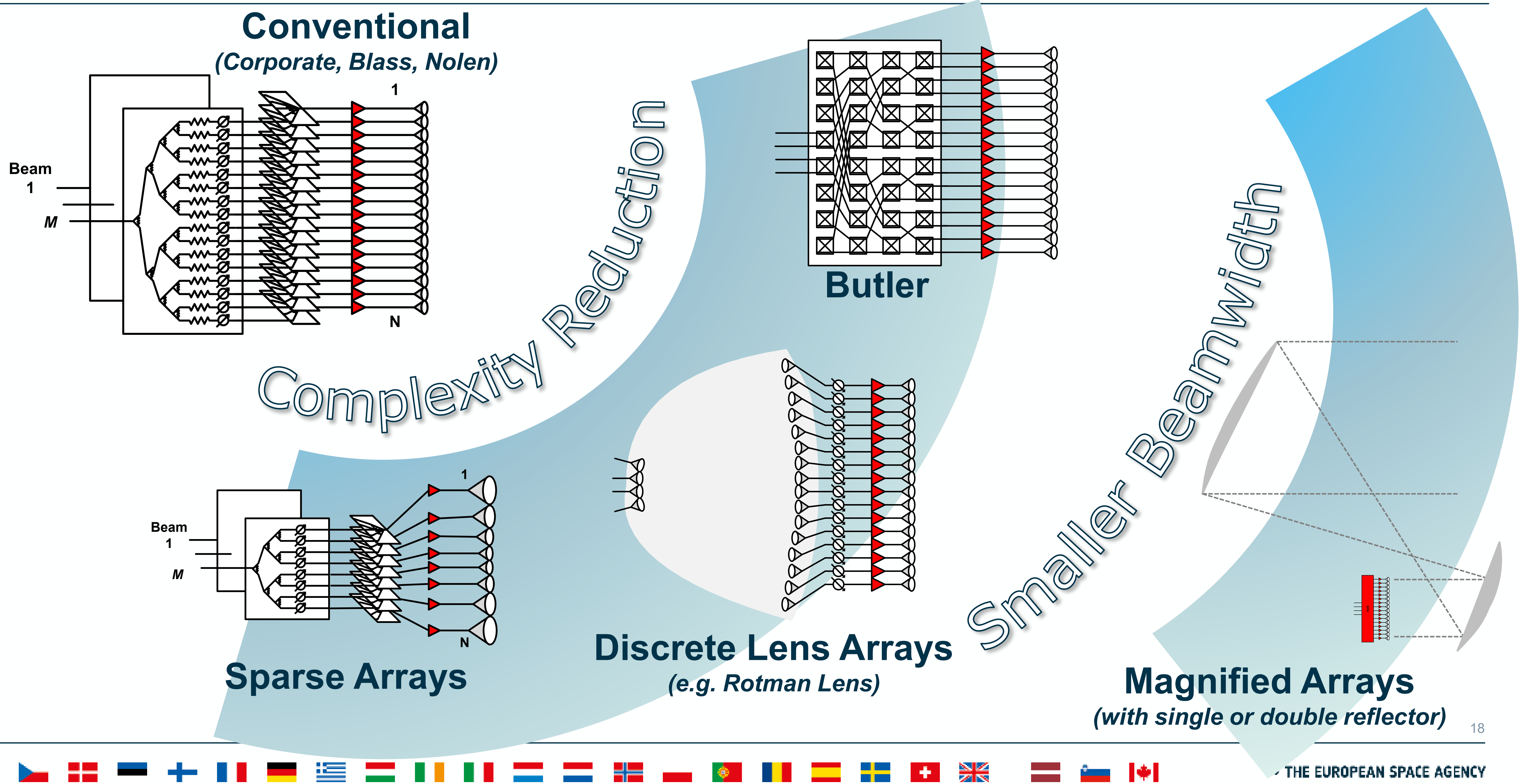


Ka-band array built from identical 3D printed monolithic clusters for GEO active array (Courtesy of Swissto12)



Ka-band array concept for GEO (Courtesy of Thales Alenia Space France)

Active Multibeam Antennas / Beamforming

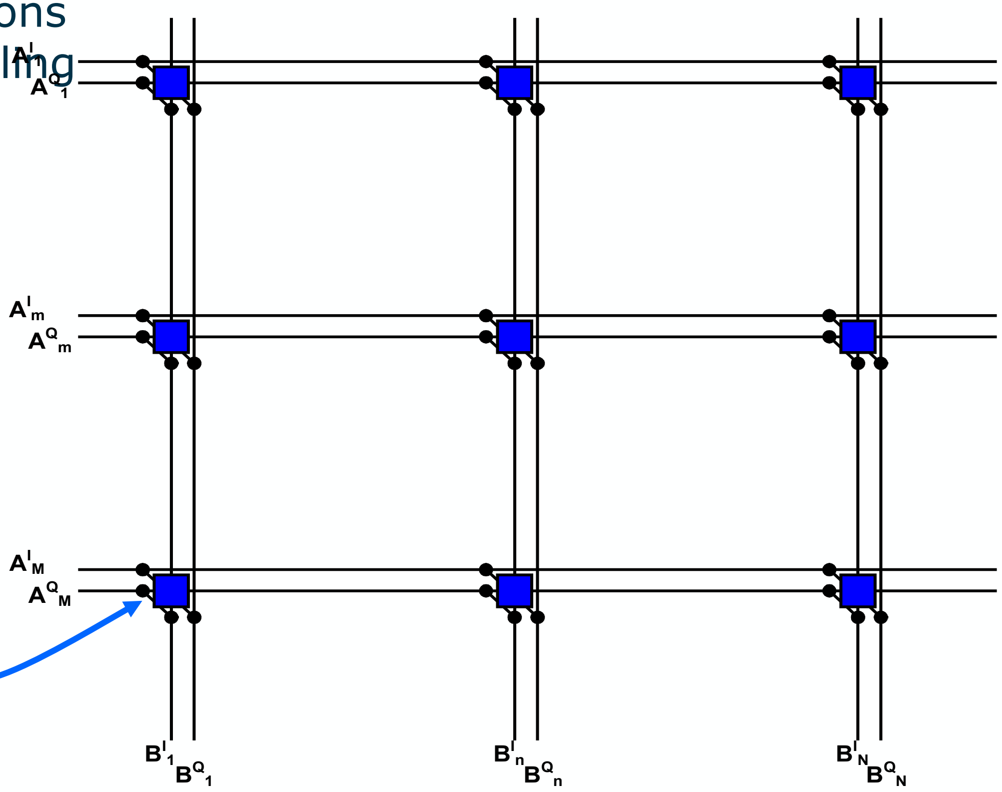


The other option: Digital Beamforming

- In digital beamforming, the operations of phase shifting and amplitude scaling for each antenna element, and summation for receiving, are done digitally.

I,Q samples of the beam signals

Complex Multiplier and Adder



Digital Beamforming - Features

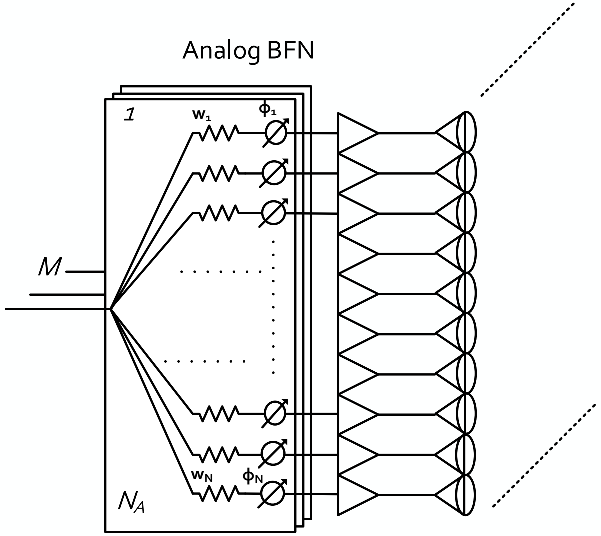
DBF can offer the following non-exhaustive list of the features

- Beams can be individually formed, steered and shaped.
- Beams can be assigned to individual user.
- Beamforming strategy can be software upgraded.
- Interference can be minimised implementing Adaptive Beamforming.
- DSP techniques (filtering, multiplexing, demodulation, signal information extraction, performance optimisation, etc.) can be integrated.

Digital Beamforming Antennas, "the Ultimate Antennas"

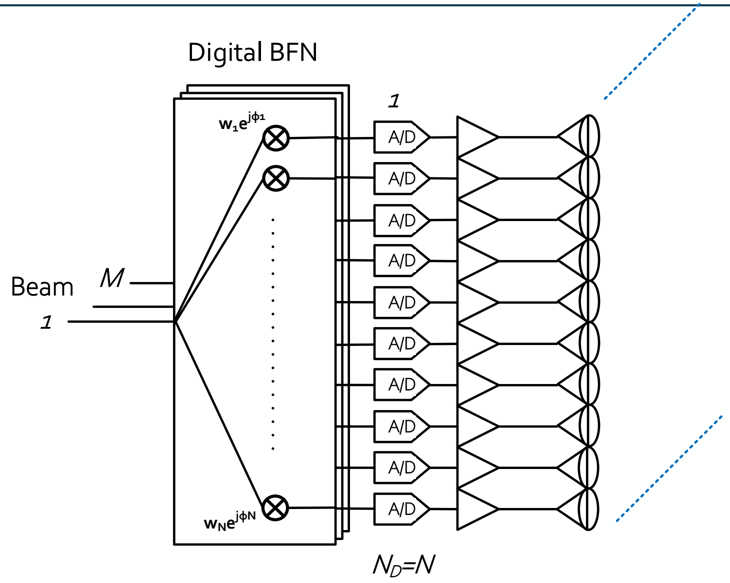
A.J. Viterbi

Analog or Digital beamforming? Both!



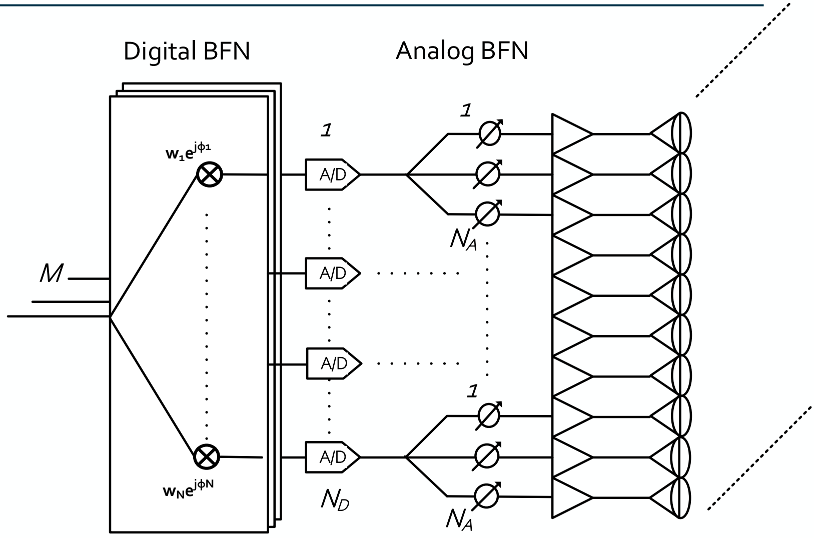
Analog BFN

- Cost
- Power consumption
- High number of components for large number of beams
- Mass/Volume
- Precision/Accuracy inferior wrt DBF
- Reduced reconfigurability wrt DBFN



Digital BFN

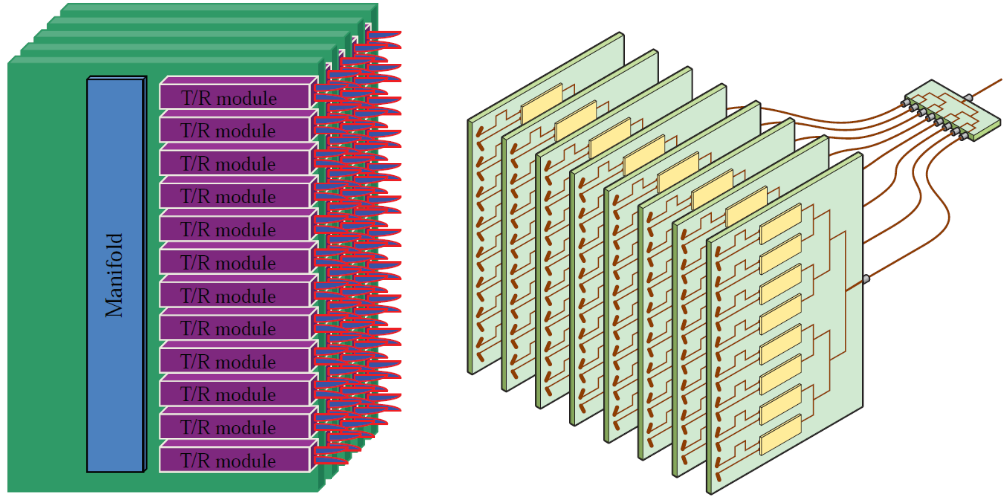
- High flexibility/reconfigurability
- High precision
- High power consumption
- Cost



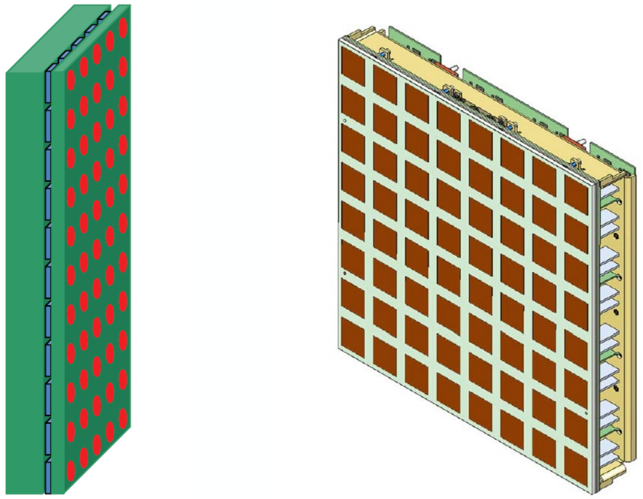
Hybrid BFN

- Good balance between power consumption and flexibility
- Reducing Nr of digital ports (i.e ADCs) with respect to full DBFN
- Complexity/Cost

Brick vs Tile Architecture



Brick Pictorial Example



Tile Pictorial example

- Tile Architectures are in principle preferred for size and mass reasons, however practical limitations on technology readiness, power consumption and thermal dissipation lead often to the implementation of Brick Architectures
- Frequency and Tx power per element are also major drivers for the architecture selection
- Typical GEO payloads with active antennas are currently based on the brick architecture, LEO payloads are also moving towards tile architecture

Transparent On-Board Processors

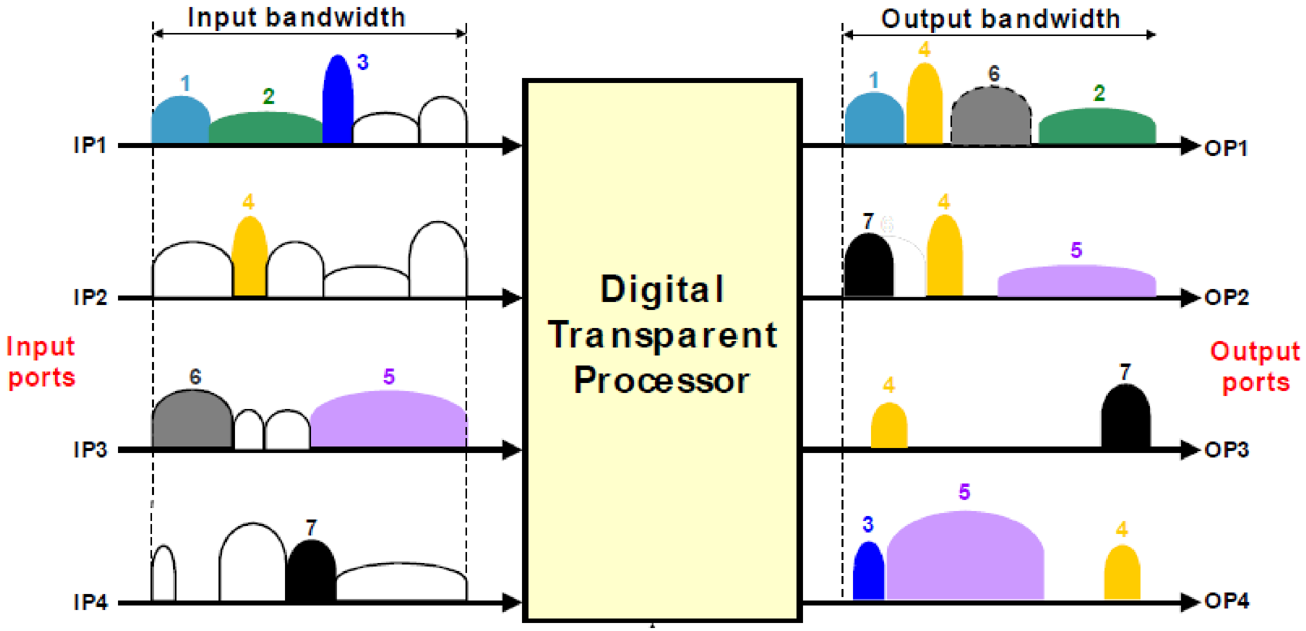
Digital Bent-Pipes

- Offer an alternative to the analog filtering, routing and frequency conversion.
- More efficient use of space resources
- The same design can be easily adapted to different customer requirement reducing non recurrent development costs.

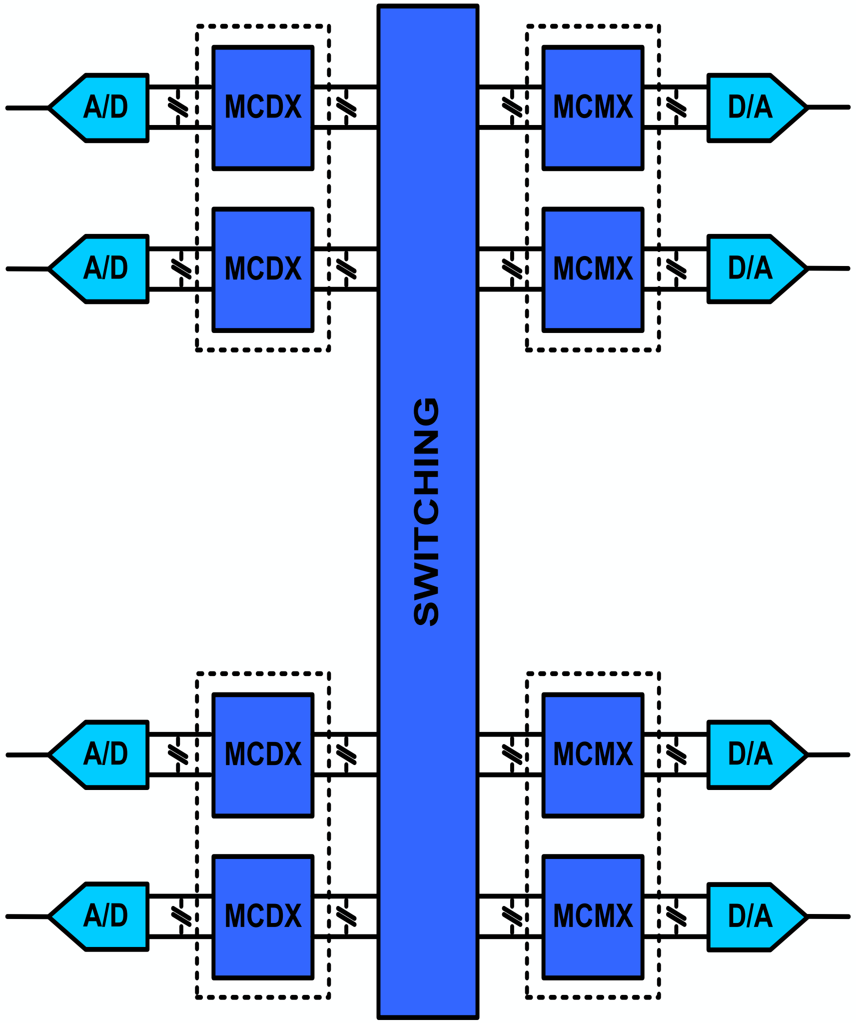
Intensive and continuous support of the European Space Agency on:

- Co-design of architectures and algorithms.
- Technological building blocks (ASICs, ADCs/DACs, HSSLs, packaging)
- Development qualification and in-orbit demonstration

Now a commercial reality!



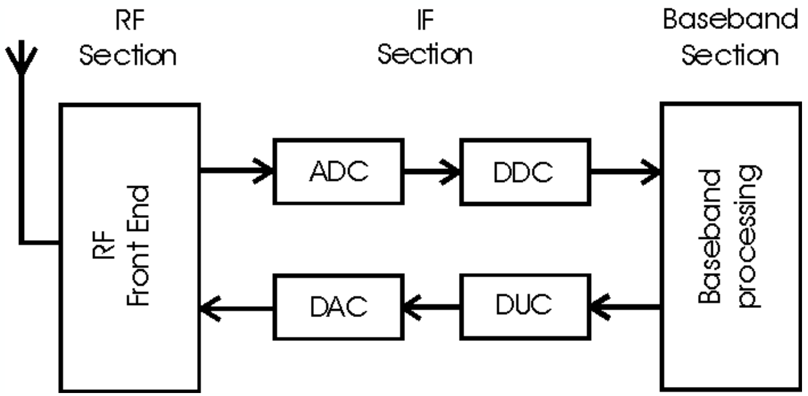
OBP Key Enabling Technologies



- High-speed and low-power A/D and D/A converters,
- High-speed serial links between components (intra-boards and inter boards/equipment),
- Radiation-hardened ASIC technology (high integration, low voltage, low power),
- High density modular packaging,
- Thermal Management,
- Processor architecture/algorithm optimisation (to minimise complexity burden, interconnects, power consumption, etc),
- FPGAs (SoC/RFSoC/SiP/etc…) and DSPs for reconfigurability.

Evolution of Software Defined Radios

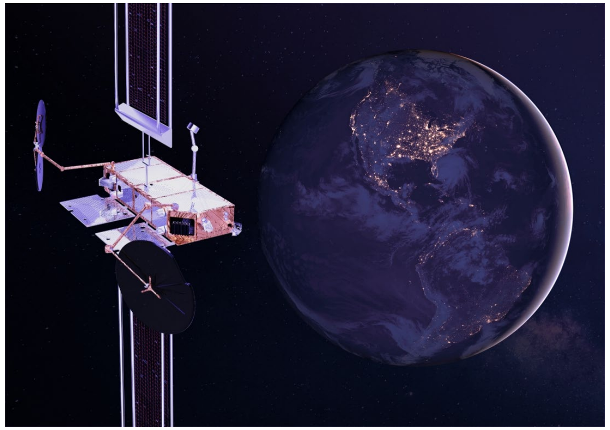
Challenges for Software Defined Radio Systems



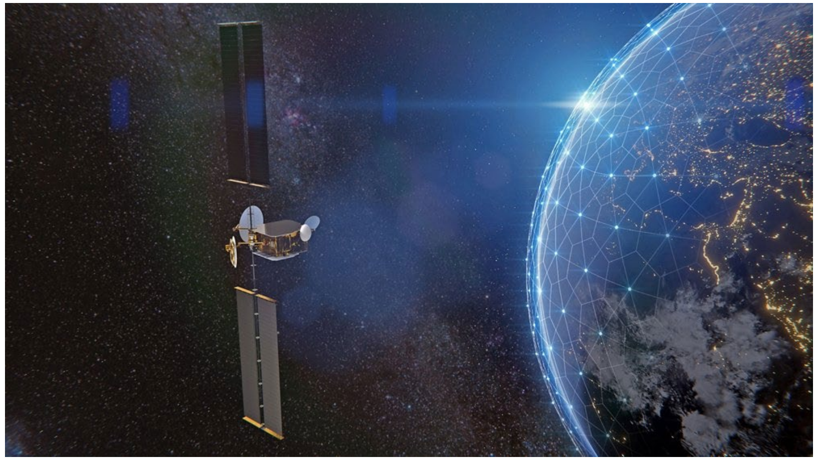
- Increased Component Density
- Higher Device Complexity
- Higher-Speed Data Converters
- Faster Device and Board Interfaces
- Development Cycles
- New Technology Insertion
- Design Portability
- Reliability and Maintainability
- Life Cycle Management
- SWaP-C

Recent European Mid-Class Flexible Payloads

- Recent European platform and payload developments (e.g. ADS Onesat and TAS SpaceInspire) target indeed mid-class fully reconfigurable payloads, based on digital transparent processor, distributed amplification and active antennas.
- These payloads will be equipped with latest digital processors developments with also digital beamforming capability
- Software defined, moderate/high capacity, agility, in-orbit reconfiguration, flexible coverage, proven serial production
- Obviously flexibility comes at a cost, they are not able to achieve (yet) very high throughput capacity per satellite (e.g. about 200-300Gbps in FW link)



SpaceInspire artistic impression (Thales website)

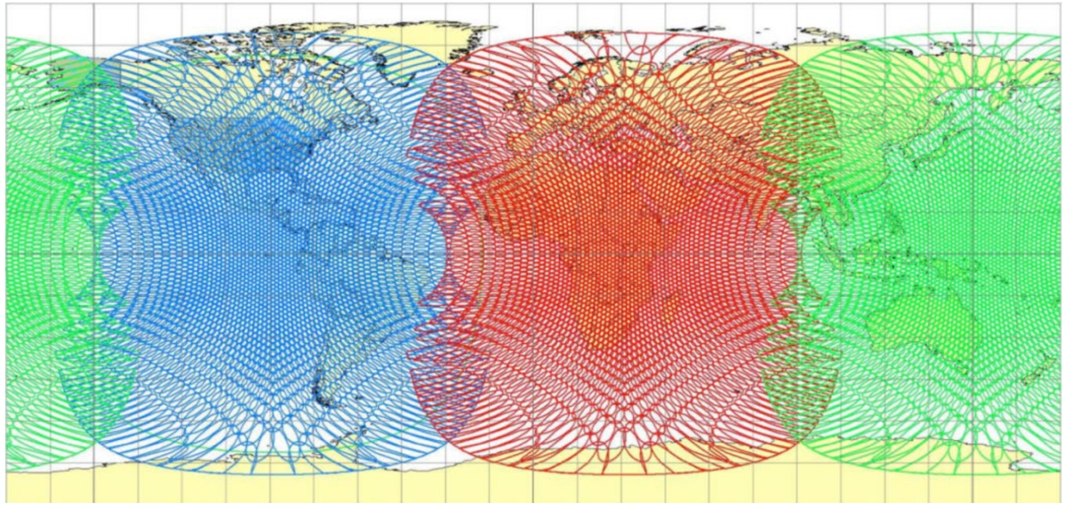


Onesat artistic impression (ADS website)

Non-GEO constellations: a cost effective solution?

Recent years have seen the re-proposing of the well-known trade-off between GEO and non-GEO:

- GEO: 3 GEOs provide global coverage except polar regions
- MEO: O3b MEO provides global coverage except polar regions with 4-20 satellites
- LEO: OneWeb/Lightspeed/Starlink provide global coverage with hundreds to thousands satellites with:
    - + Limited latency (30-50ms wrt 600-800ms for GEO orbit)
    - + Smaller satellites / series production
    - + Larger # satellites
    - + Possible polar areas coverage
    - - Shorter lifetime, high (total) launch cost
    - - User terminal tracking antenna
    - - More complex infrastructure deployment and management
    - - More difficult spectrum sharing



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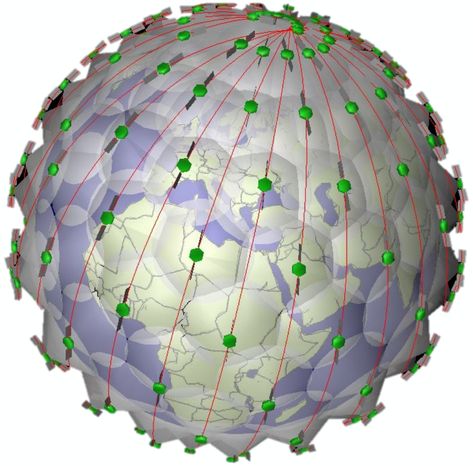
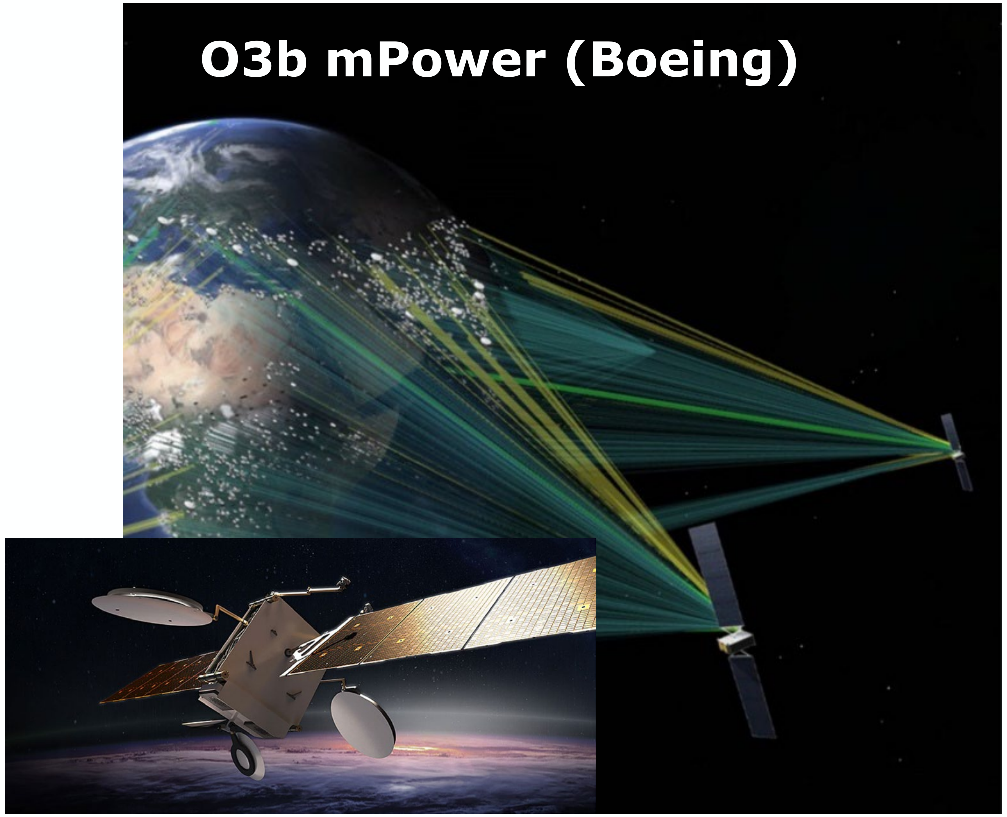


The Challenge until now … Non GEO Constellations

Recent Broadband systems are emerging in LEO and MEO

Operator	Satellite system (deployed)	Spectrum	Technology	Operational	Services
Space X (Starlink)	12000+ (3580)	Ku-band	Proprietary	Yes	Broadband
OneWeb	648 (542)	Ku-band	Proprietary	TBD	Broadband
Kuiper	3236 (0)	Ka band	Proprietary	Estimated 2024	Broadband
Galaxy Space	1000 (7)	Q/V spetrum	Proprietary	TBD	Broadband
Boeing	147 NGSO (1)	V band	Proprietary	TBD	TBD
Inmarsat	14 GEO (14)	TBD	Proprietary	TBD	Broadband to IoT
Telesat	188 (2)	C, Ku, Ka bands	Proprietary	TBD	Broadband
Echostar	10 GEO (10)	Ku, Ka, S bands	Proprietary	Yes	Broadband
HughesNet	3 GEO (2)	Ka band	Proprietary	Yes	Broadband
Viasat	4 GEO (4)	Ka band	Proprietary	Yes	Broadband

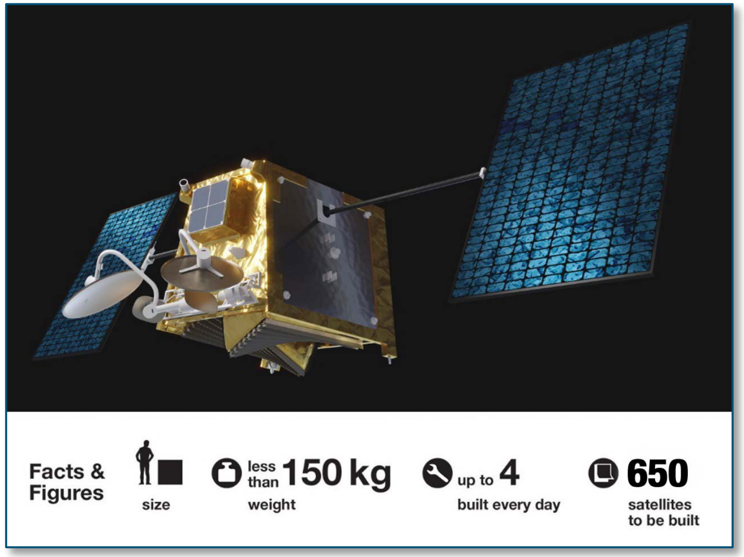
Source/Credit: 5G Americas

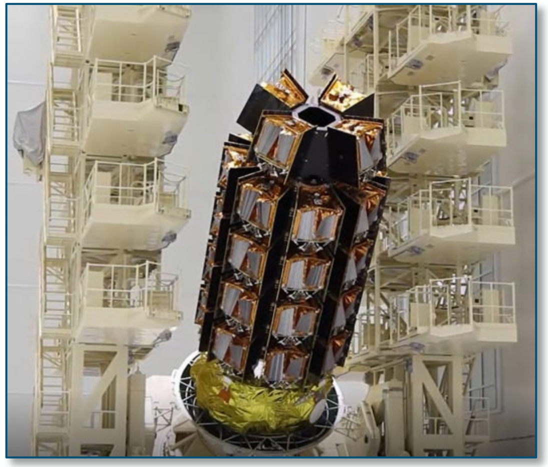


- MEO System
- Supported by Software Defined Radio Boeing 702X satellites
- Digital beamforming performed (claimed up to 5000 beams per satellite)

The Challenge now and Ahead … Mega Constellations

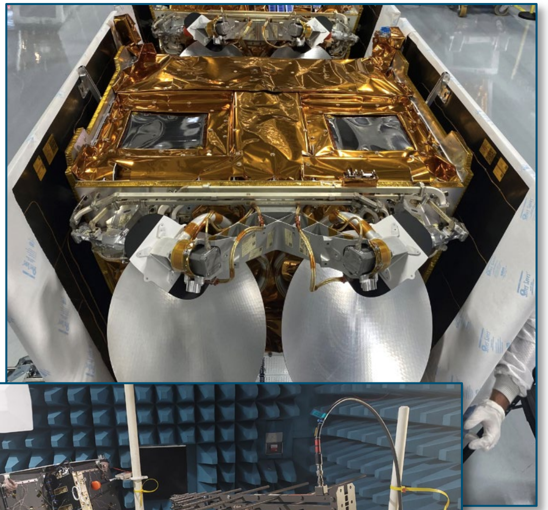
Oneweb

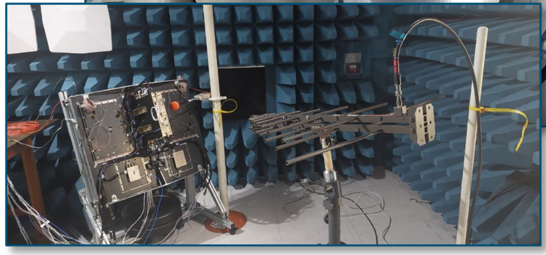




Credit: Oneweb, ADS, ArianeSpace

- >618 satellite launched to date
- Sat: 150kg, 1kW
- Ku-band non-active antennas
- Next generation Oneweb 2nd gen will likely increase satellite size (~500kg) and upgrade payload capabilities based on active antennas and digital processors





Credit: JoeySat satellite, (demonstrator for 2nd gen)

The Challenge now and Ahead … Mega Constellations

Lightspeed - Telesat

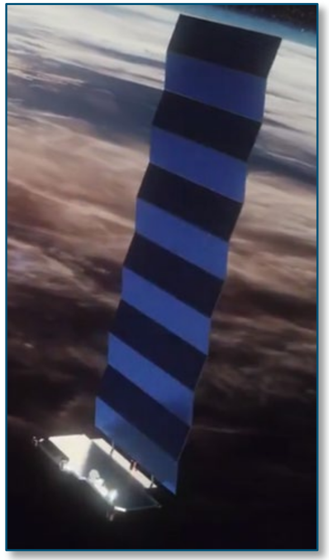
Source: Telesat, MDA

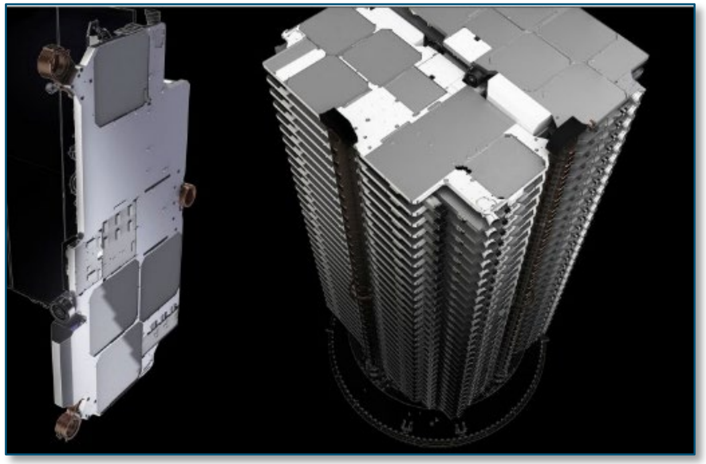
Main Facts:

- 198 satellites on polar orbit
- payload based on:
  - Ka-band active phased array antennas
  - Digital processor,
  - Digital beamforming, and beam hopping
  - Sat Class: ~750kg, ~2-3kW

The Challenge now and Ahead … Mega Constellations

esa



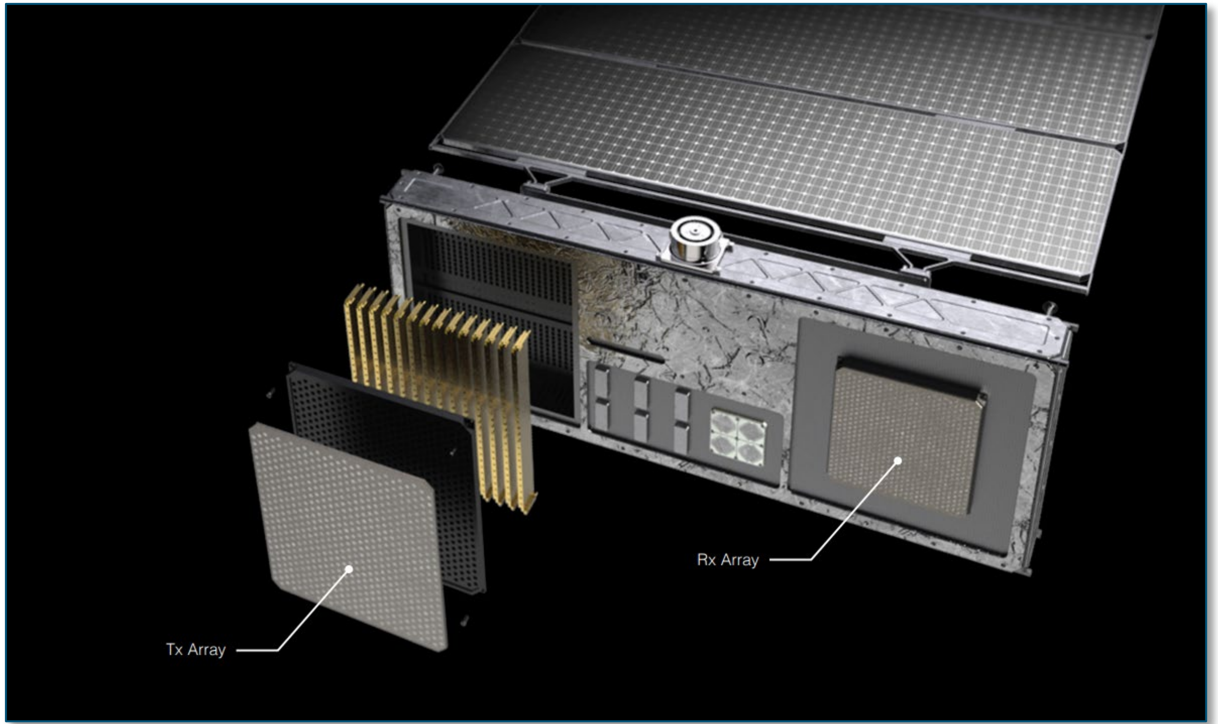


Starlink

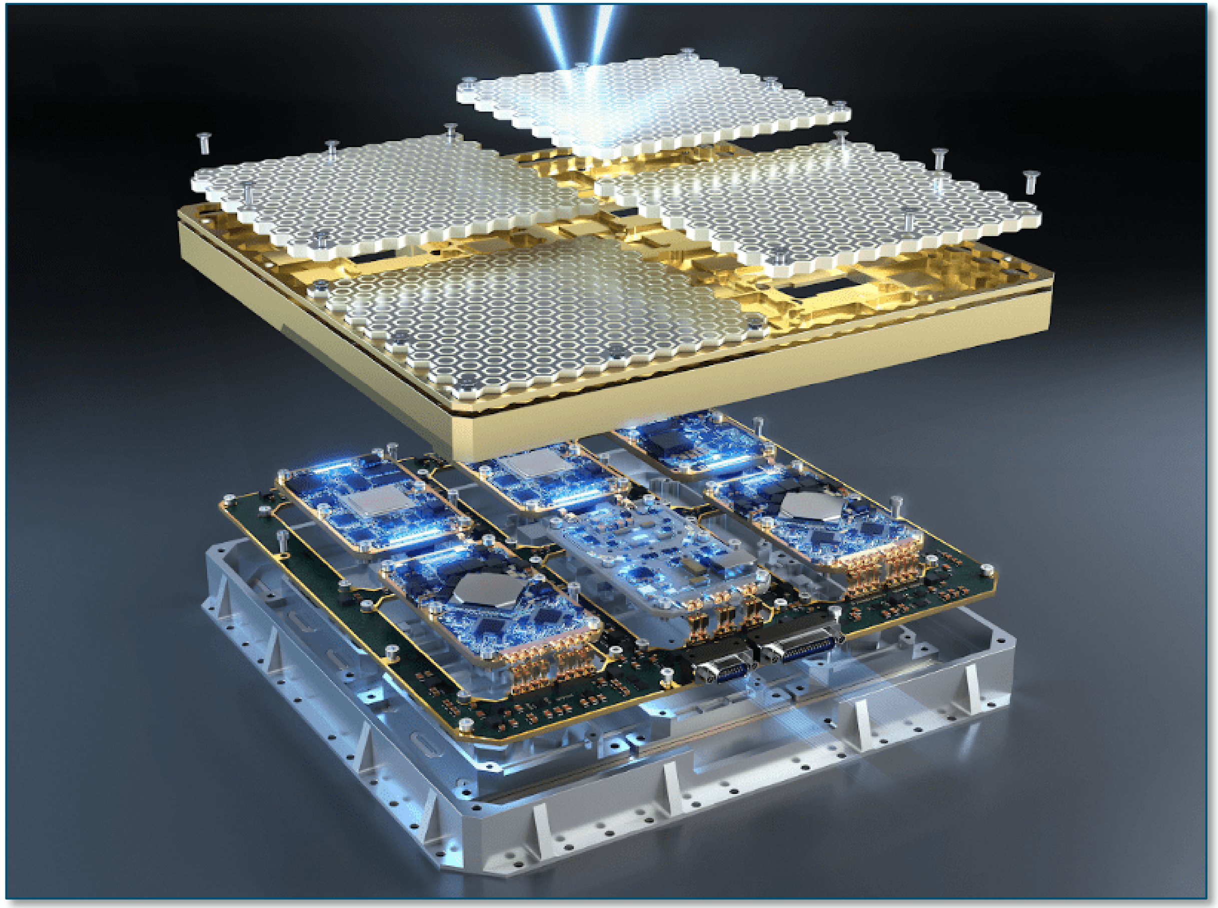
Starlink high level facts		
Mass	260kg	
Payload	Phased Array Antenna based Ku-band, ~600W	
Dimensions	Stowed	2.8m x 1.5 m x 0.23m
	Deployed	P/F:3.7m x 1.5m x 0.1 m SA: 2.8 m x 8.1 m
Launch	Falcon 9; 60 sats/launch	

- About 4000 satellites launched so far!
- Starlink 2nd gen will feature much larger satellites. V2 mini satellites have been recently launched

Space Active Antenna Example outside Europe



Pictorial Representation Ka-band active antenna , Source: Cesium Astro



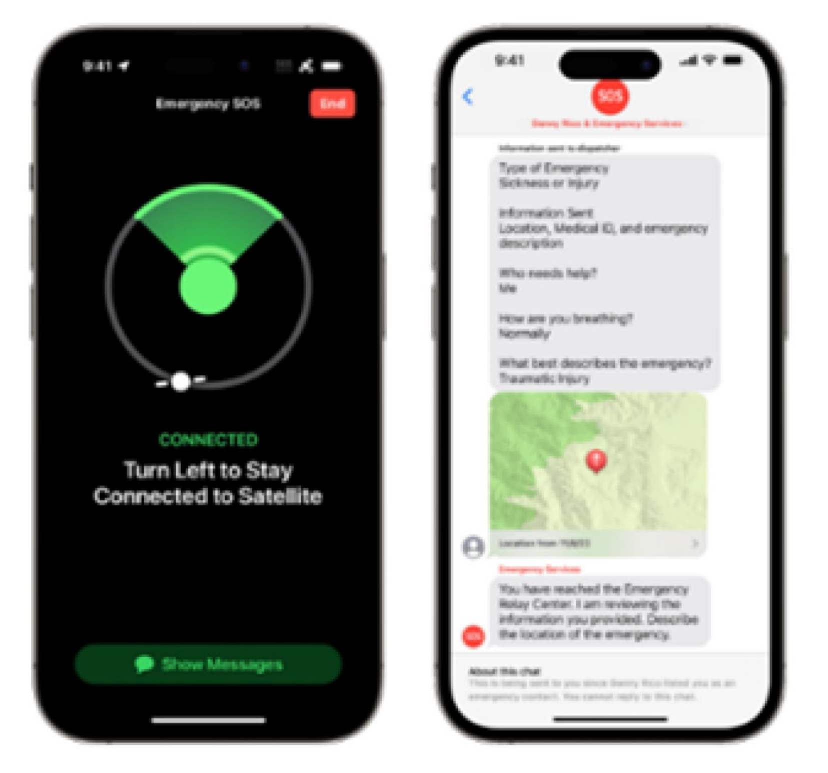
Low-Profile antennas combining analog RF and digital functions

Direct to Handheld and NB-IoT - Status

Two-Way Messaging

	Apple	Qualcomm	MediaTek	Samsung	Huawei
Phone Availability	iPhone 14 series (Now available)	Honor, Motorola, Nothing, OPPO, vivo, Xiaomi (To be available in 2023 H2)	Motorola Defy 2 (Available in 2023 Q1), CAT S75	?	• 2-way: P60 series, Mate X3 series, nova11 Ultra; • 1-way: Mate 50 series, Mate Xs series (Now Available)
Features	One-way SOS messaging	Two-way SOS messaging	Two-way SOS messaging	Two-way SOS messaging	One & Two-way SOS messaging
Satellite Operator	Globalstar	Iridium	Inmarsat Skylo	?	Deidou
Constellation	LEO	LEO	GEO	LEO	GEO
Implementation	Proprietary	Proprietary	3GPP R17 NTN standard	3GPP R17 NTN standard	Proprietary

(Source: R&S, Apple, Qualcomm, MTK, Samsung, Huawei)

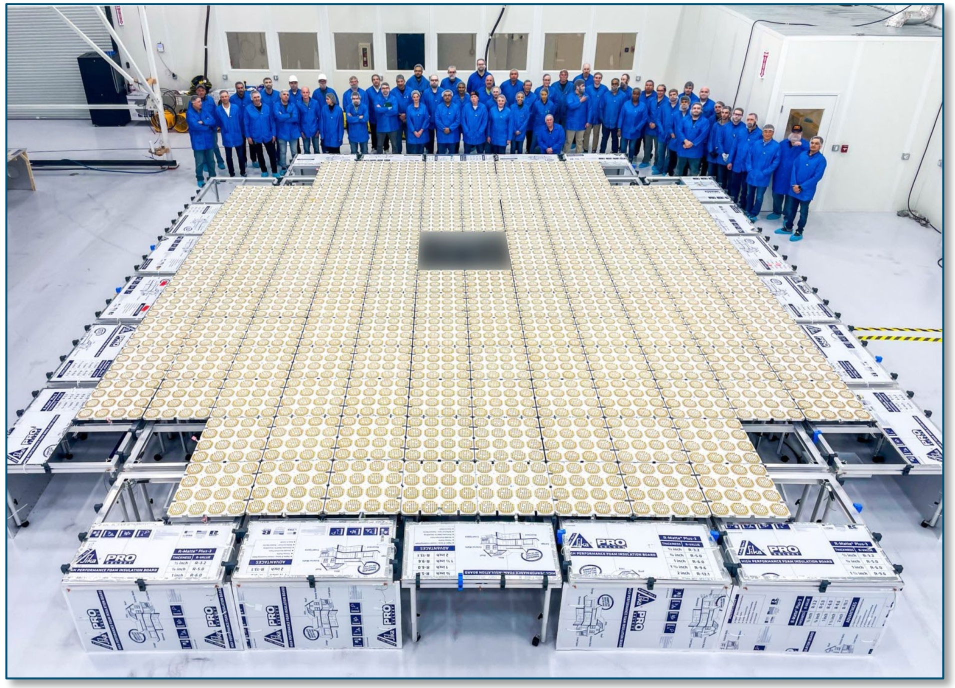


Direct to Handheld and NB-IoT - Status

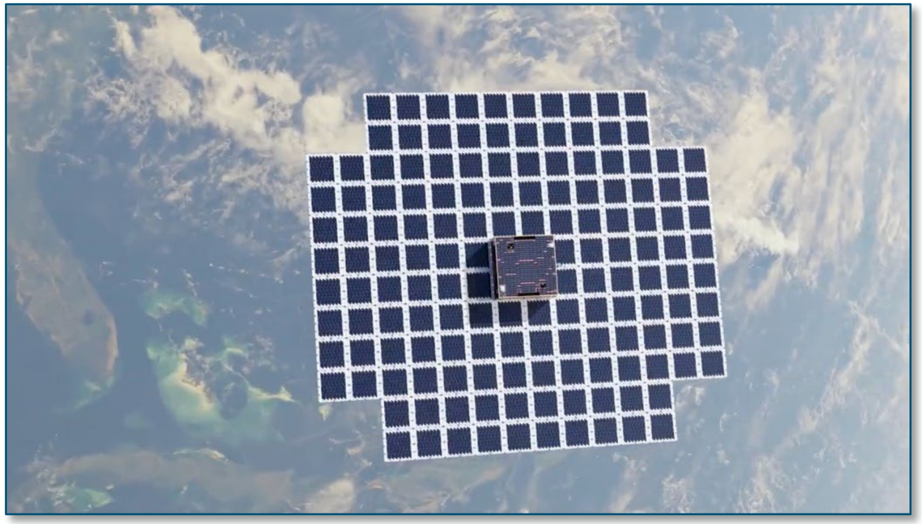
A Broadband Applications

Main Facts:

- 64m^2 aperture
- 3GPP Frequency: 750-850MHz
- Enables data-rates ~10Mbps



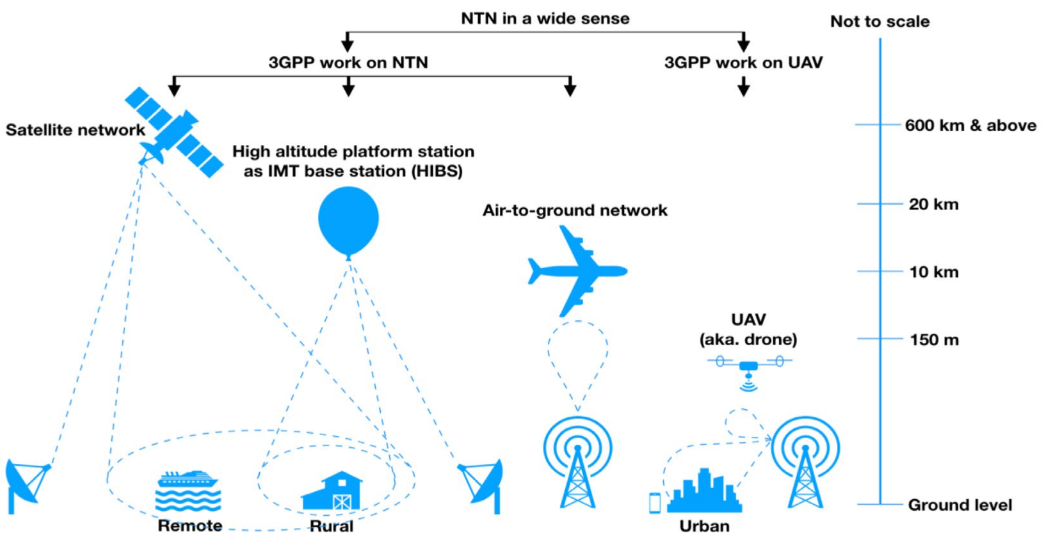
Source: AST-Science Spacemobile, BlueWalker 3 prototype satellite



On April 25 2023, made the world's first space-based two-way telephone call with unmodified smartphones (a Samsung Galaxy S22 and an Apple iPhone) using the satellite.

5G NTN Non Terrestrial Networks

- Use of Satellites being Standardized within 3GPP as part of 5G, contributing to the 5G NTN
- Integration of Terrestrial Networks and Non-Terrestrial Networks to provide enhanced mobile broadband (eMBB) to consumer mobile phones and IoT
- Rel17 specifies L-band and S-band, Rel18 introduces >10GHz bands



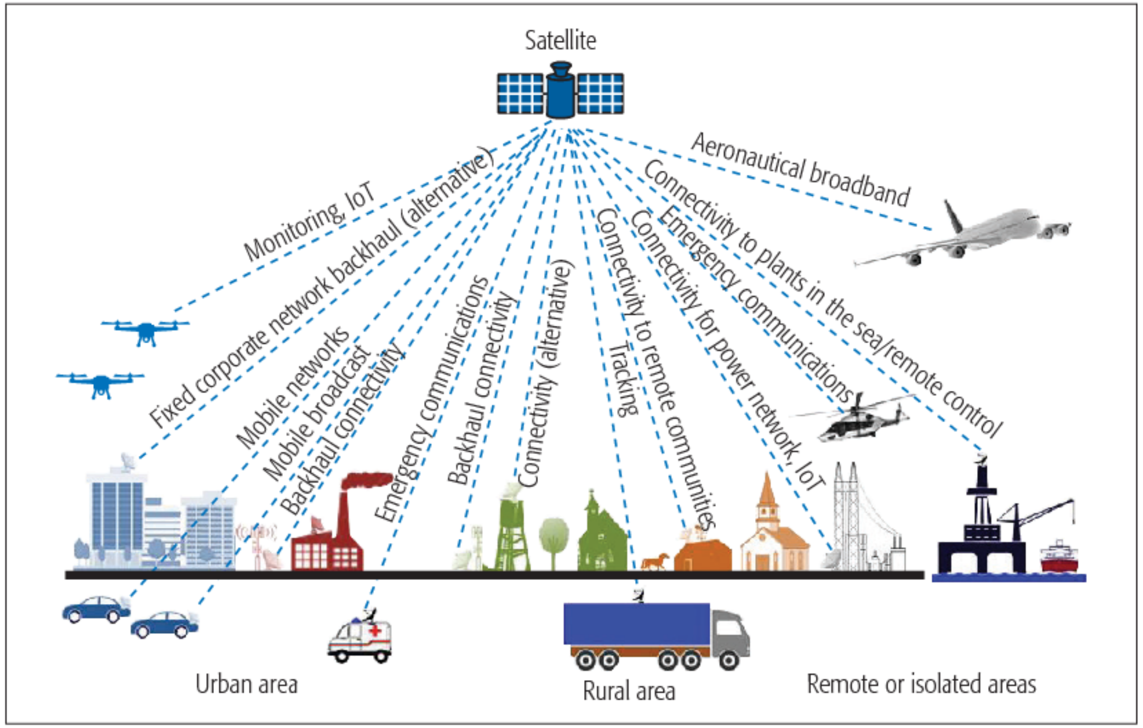
Source: 3GPP

	R15	R16	R17	R18	Beyond R18
Stage	NR-NTN Study Item (SI)	NR-NTN Study Item (SI)	NR-NTN Work Item (WI) IoT-NTN Study Item (SI) & Work Item (WI)	NR-NTN & IoT-NTN Work Item (WI)	Future
End of Release	2018	2019	2022	Work-in-progress	May focus on: • Regenerative Payload Architecture • Support UE w/o GNSS capabilities • Multi-Connectivity & carrier aggregation btw satellite orbits or btw satellite & mobile access • NTN-TN spectrum coexistence
Technical Reports (RAN/SA/CT)	TR 38.811	TR 38.821 TR 22.822	TR 38.821 Updated (NR-NTN) TR 36.763 (IoT-NTN) TR 23.737 TR 28.808 TR 24.821	TR 22.926 TR 28.841 TR 38.863 TR 38.882 TR 23.700-28/27	
Summary	Study on NR support NTN including channel model, deployment scenarios, potential key impact areas	• Study on necessary features enabling support NR-NTN • Identify use cases & requirements	• Specify NR-NTN (focus on Transparent payload architecture & w/ GNSS-capable in UE) • NTN based on LEO & GEO • Study on NB-IoT/eMTC support for NTN including scenarios & necessary changes • Specify requirements & architecture & management of satellite access in 5G • Frequency below 6GHz (S-band & L-band)	• Enhancement for NTN coverage • NTN deployment above 10 GHz • Network verified UE location • Mobility & service continuity btw NTN & TN	

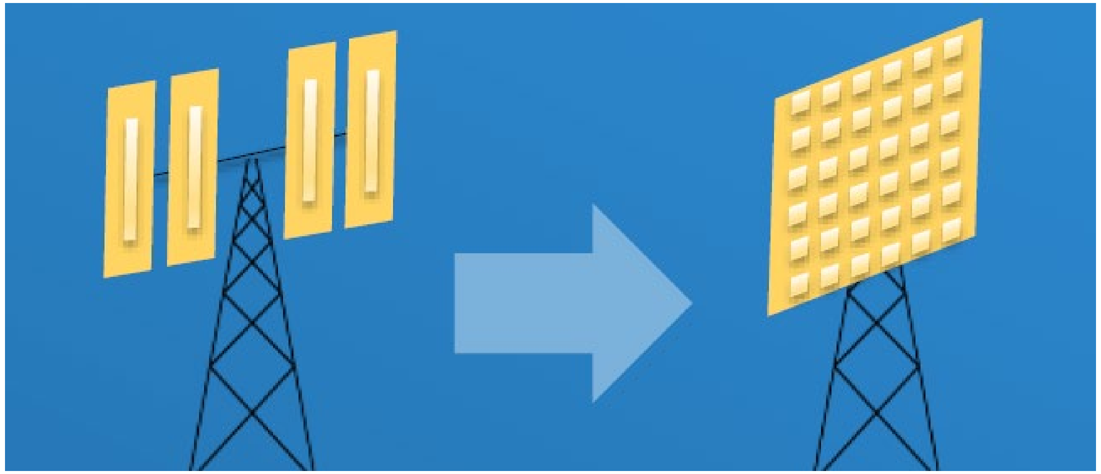
(Source: IEEE, Nokia, Ericsson, 3GPP, Zenn, GSA, MTK, Thales)

Integration and Convergence and with 5G

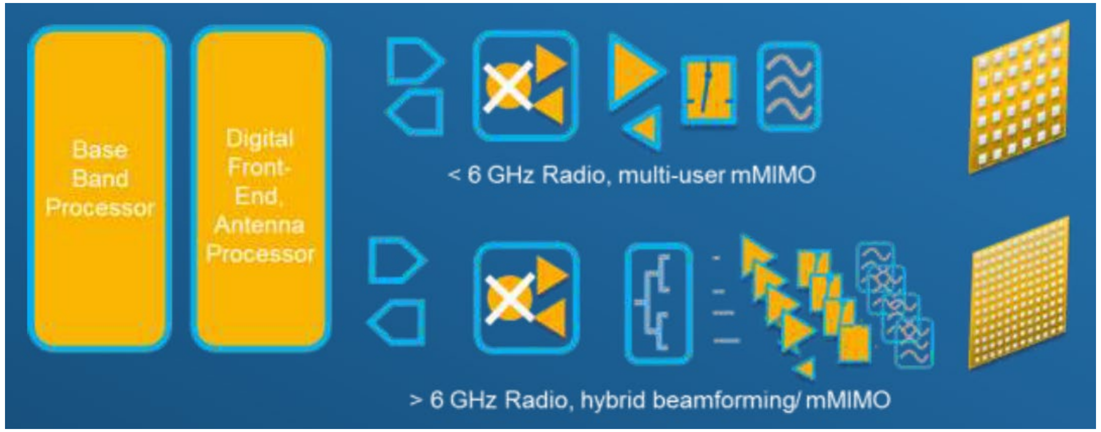
Satellite Use Cases



Convergence of Technologies



Active Antennas



Digital Signal Processing

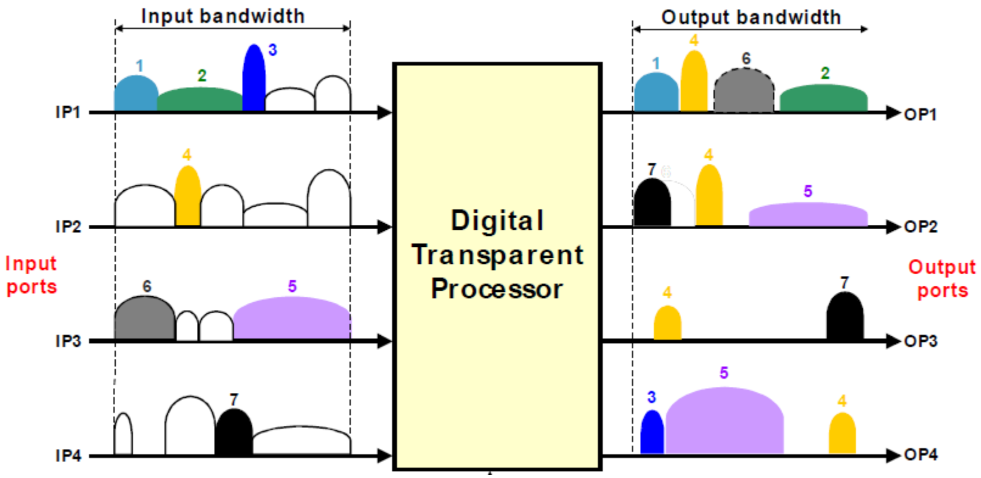
Digital Processors: key enablers for the functionalities of current and next generation payloads

Digital Processors provide critical functions enabling flexibility:

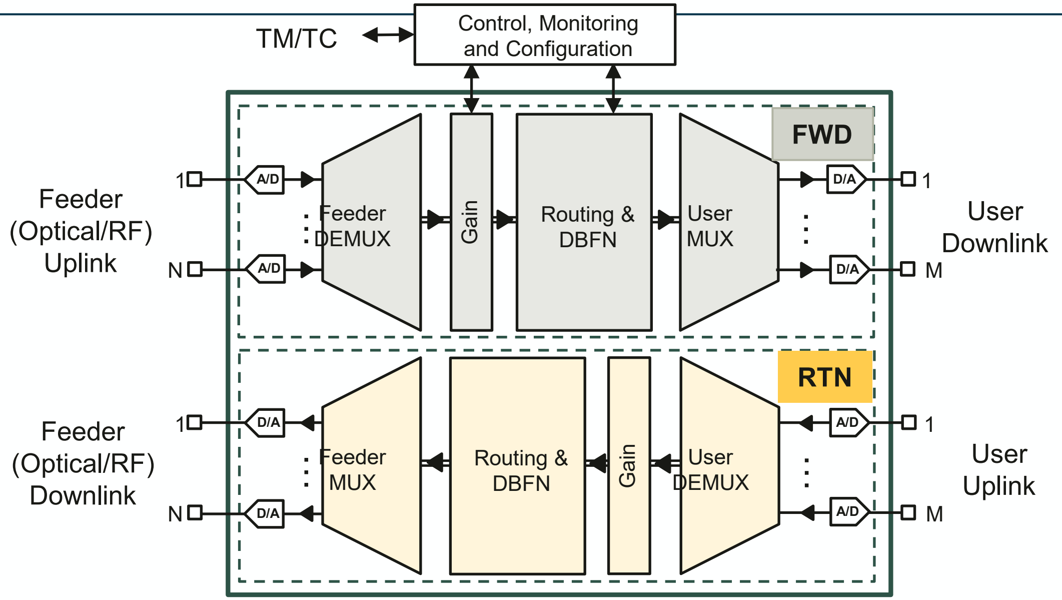
- Communication enabler between GEO, LEO, UAV and terrestrial network systems
- Digital signal/data processing via transparent or regenerative processor: channelisation, routing/switching, digital pre-distortion, digital beamforming, hopping, modem functions
- Active antenna management and beamforming control
- Inter-satellite link enabler via RF or optical links

ESA active support on:

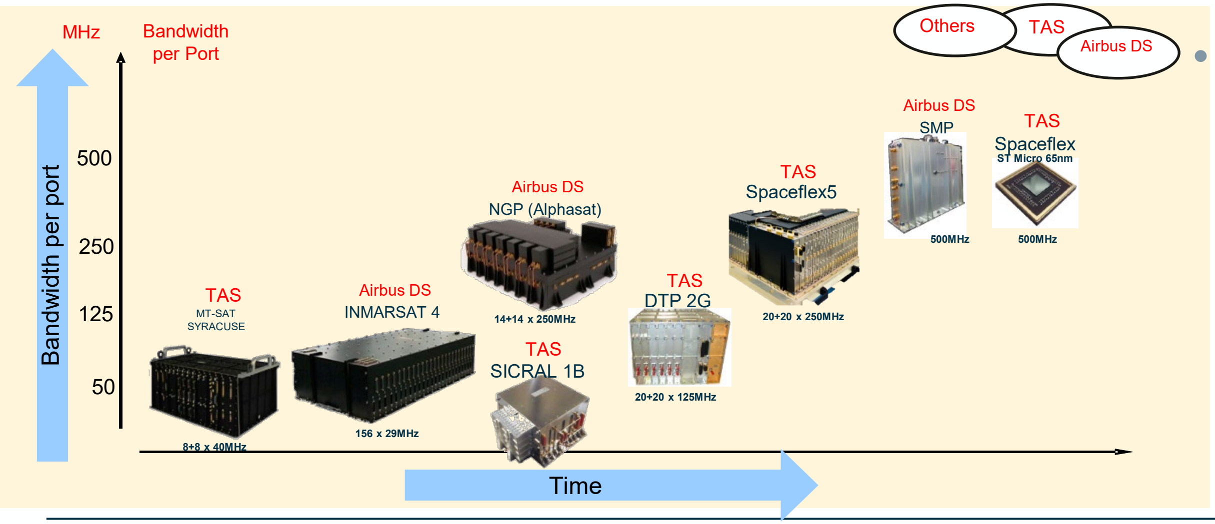
- Technological building blocks (ASICs, FPGAs, ADCs/DACs, HSSLs, packaging)
- Co-design of architectures and algorithms
- Development qualification and in-orbit demonstration



Digital Transparent OBP

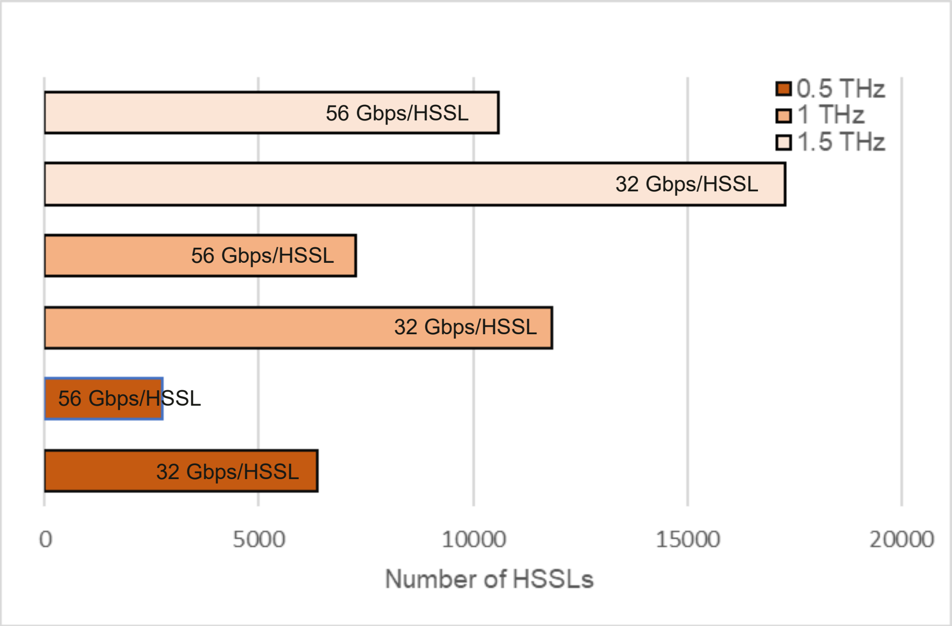


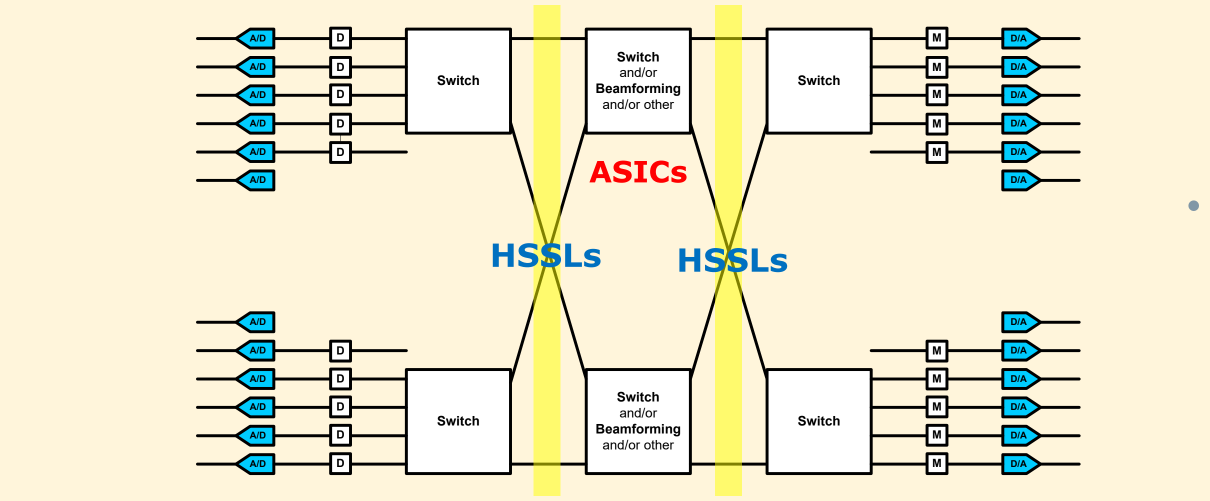
Digital Transparent OBP



- A digital transparent OBP serves as a well-established solution for demultiplexing, routing, and multiplexing signals for reception and transmission for satellites.
- In a high-throughput configuration, the digital processor can also handle a portion or the entirety of the beamforming task.
- Technology developments in High-speed data converters (ADC &DAC), transistor and packaging, interconnect improve the capability and efficiency of these processors.
- Additional processing tasks can be assigned to the OBP to perform; frequency and beam hopping, beamsteering, interference mitigation, level control, dynamic channel switching, equalisation, power control, dynamic resource management, spectrum optimisation and allocation, calibration and linearisation.

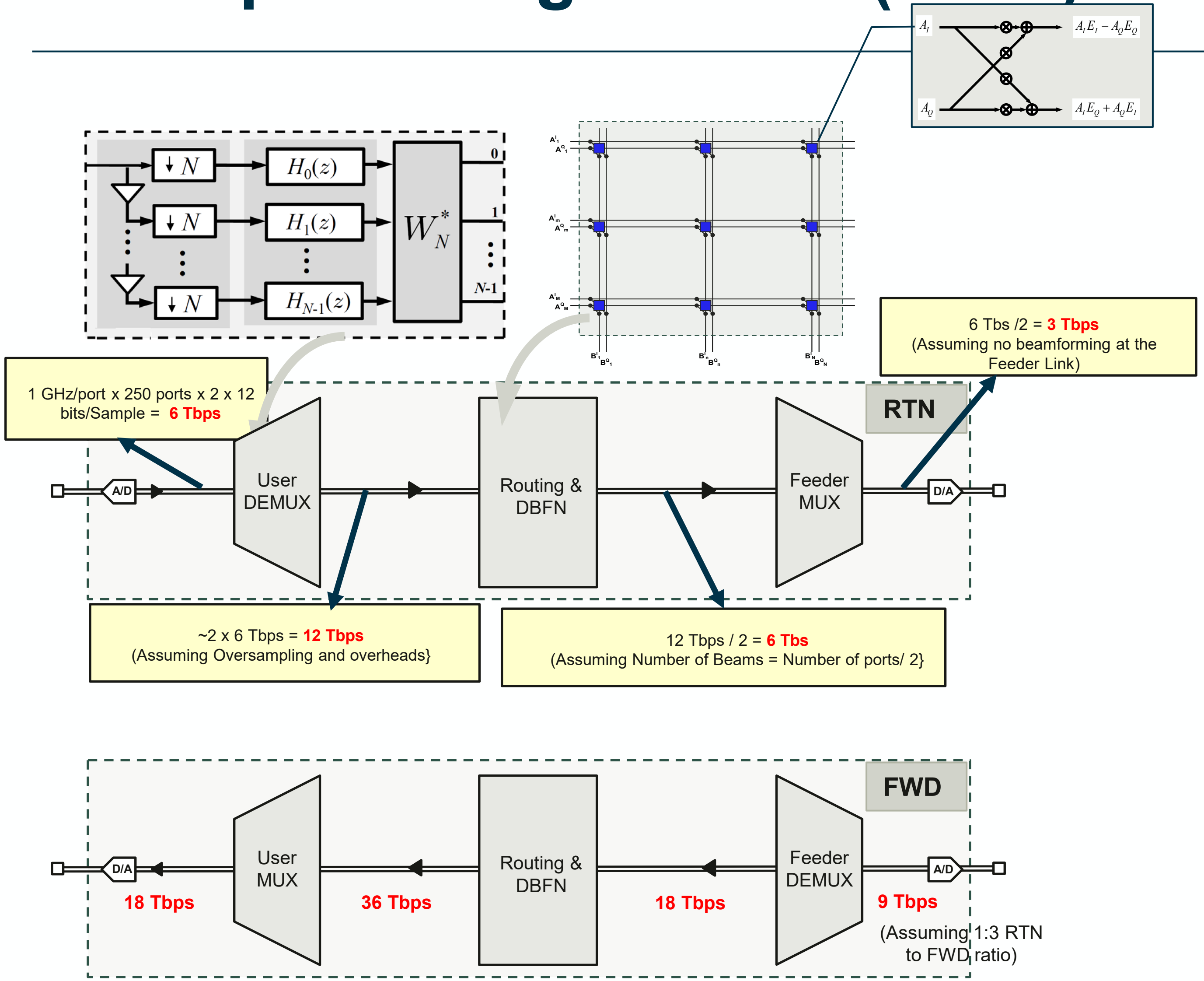
Transparent digital OBP (cont.)





- For UHTS GEO missions, custom ASIC designs are the preferred choice for conducting OBP operations due to their power efficiency. However, in a narrower bandwidth and low throughput configuration, these tasks can be supported by commercial off-the-shelf (COTS) devices, particularly state-of-the-art FPGAs.
- Typically, processing takes place in several consecutive stages and layers, tailored to accommodate various customers and missions.
- The interconnection between these processing stages, and consequently between individual processing elements, is a critical limiting factor, especially as the number of ports, beams, and user bandwidth increases. Fortunately, this limitation is becoming less restrictive thanks to advancements in interconnect speeds and the availability of a greater number of HSSLs.
- Beamhopping can significantly enhance the total system capacity in a time-multiplexed fashion. Different beams can be assigned timeslots, leading to an improved frequency reuse in addition to their spatial separation.

Transparent digital OBP (cont.)

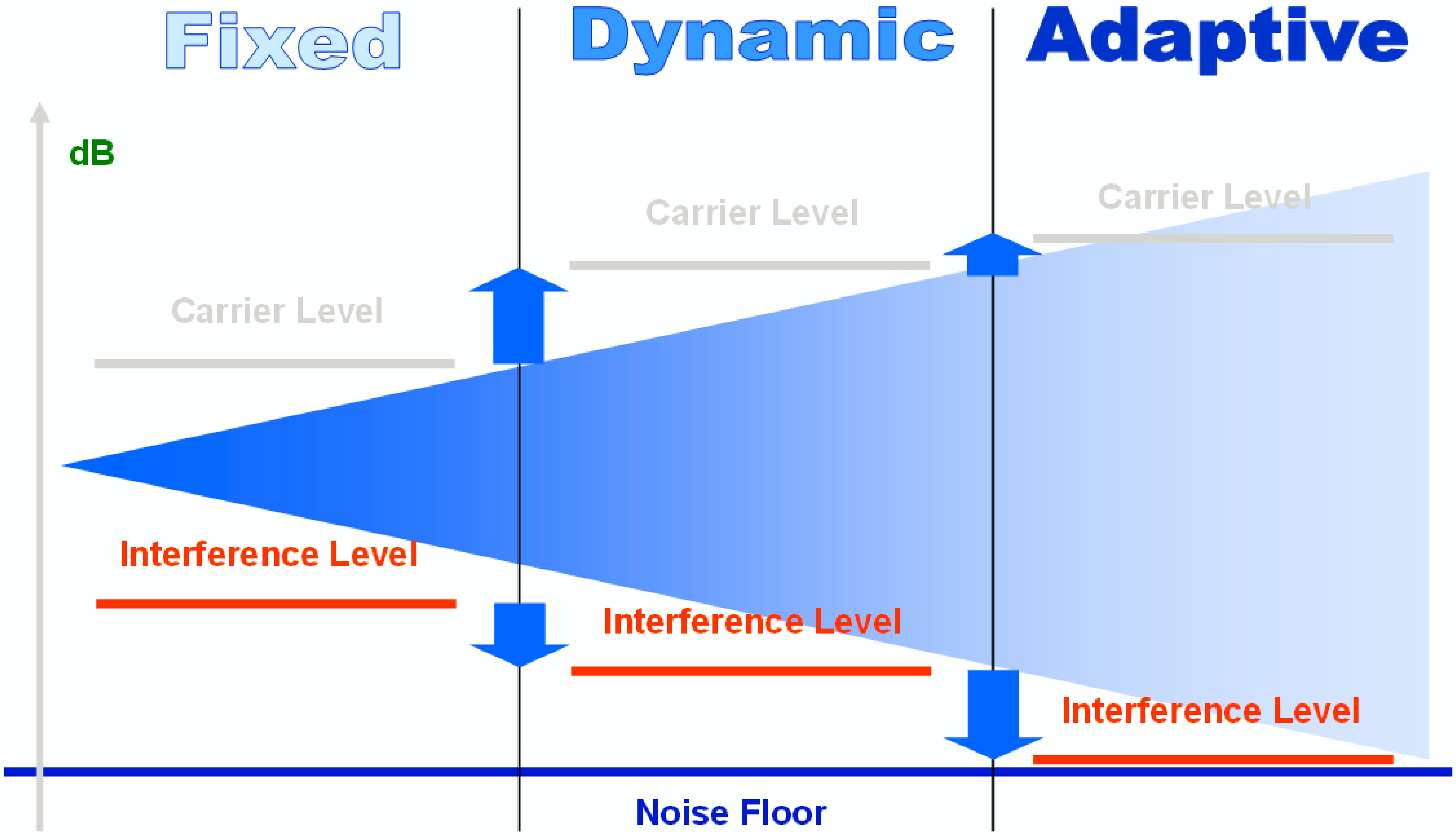


- The design of a transparent OBP becomes more challenging as the volume of data to be processed increases.

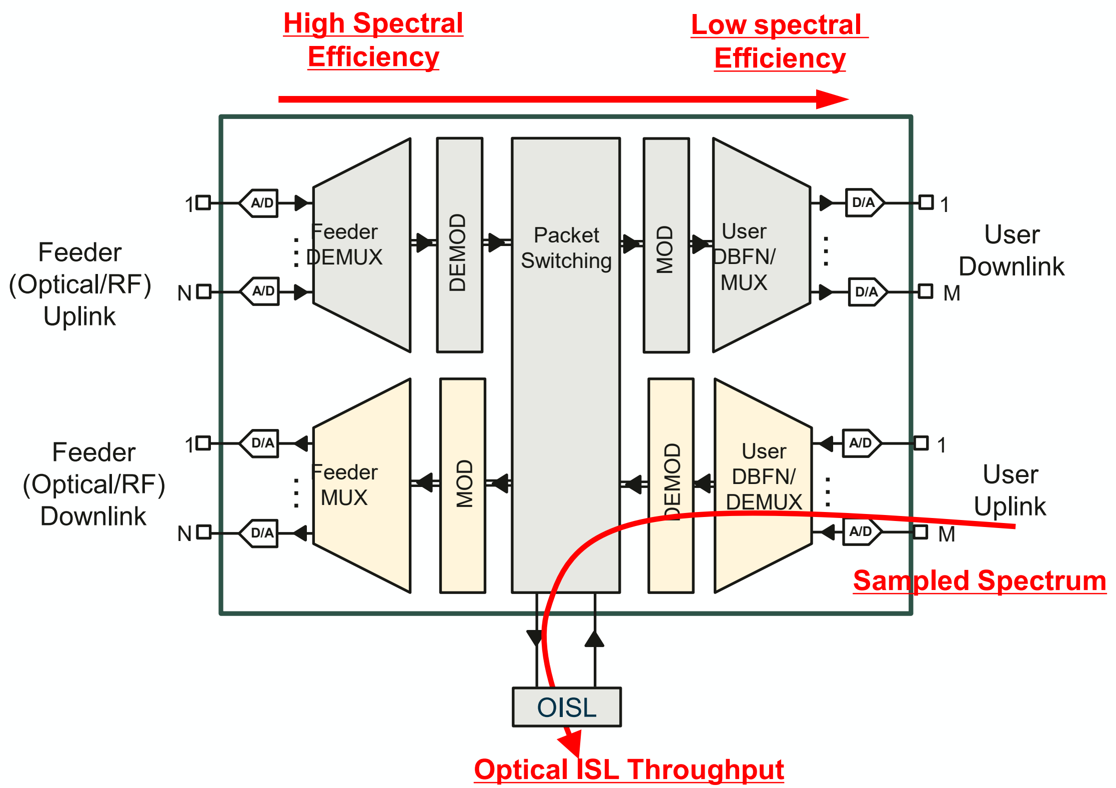
  Data Throughput = N_{port} x (2 x BW_{per_port}) x Nb_{per_sample}

- The utilisation of active antennas and full digital beamforming leads to an expansion in the number of ports on the processor, thereby increasing the data load. In contrary, lower bit resolution would be deemed acceptable when employing large antenna arrays (1000s of antenna elements).
- In digital beamforming, the operations of phase shifting and amplitude scaling for each antenna element, and summation for receiving, are done digitally. The total number of beamforming weights (i.e. multiplications) plays a key role in defining the processing burden.To carry out the complex weighting, four real multiplications and two real additions are be required. Multipliers cost much more than Adders

Transparent digital OBP (cont.)

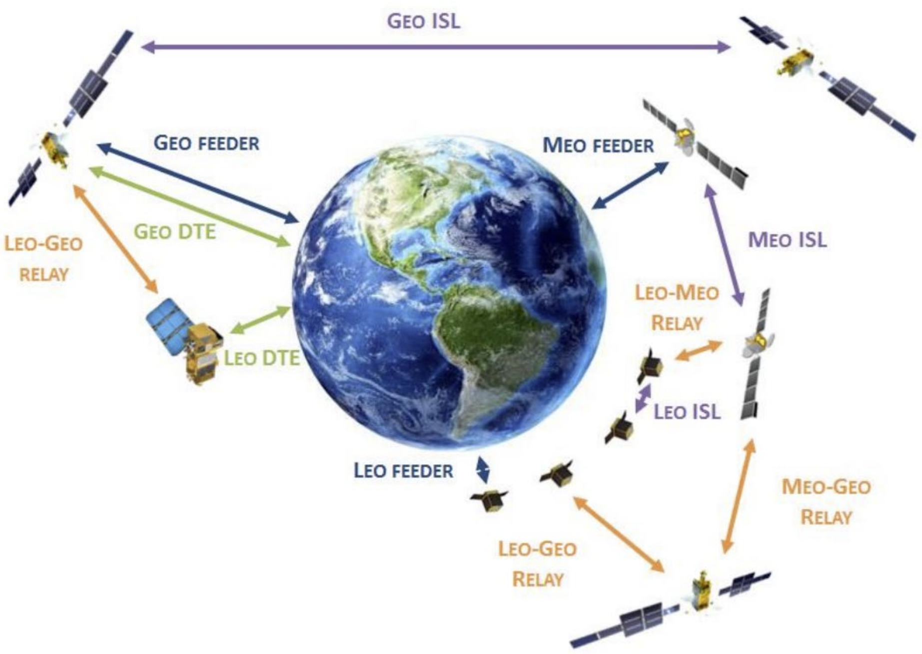


Regenerative OBP



- Regenerative processing requires additional MODEMs on board for signal encoding and decoding. They can facilitate the transformation of signals between different air interfaces too.
- This approach allows for the separation of the uplink and downlink, but it comes with the trade-off of increased complexity and power consumption in the OBP. Because the spectral efficiency of the feeder and user links differ, it's possible to support the same capacity with reduced bandwidth on the feeder link and on the ISL, thereby reducing the requirement for multiple ISLs and gateways.
- MODEMs also play a crucial role in improving the link performance by providing error correction, enhancing SNR, and optimizing the link budget.
- They could help to establish a 5G/6G connectivity on the telecommunication satellite or to support conventional DVB-S2X, DVB-RCS2 standards or custom waveforms.

Regenerative OBP (cont.)



The concept of having a MODEM onboard aligns well with the integration of the spacecraft in a network of satellites from various orbits and terrestrial networks. This approach allows for the processing of data received from ISL&RF links and facilitates rerouting to the next node in the network, thanks to the regenerative payload.

- ASICs are commercially available to deliver MODEM operations. A set of these MODEMS (of ~500 MHz each(*)) would consume only a few watts to deliver several Gbps of data. State-of-the-art FPGAs, with a good level of radiation tolerance, can also be an alternative when they are equipped with custom software and firmware as MODEM.
- Transceiver chipsets (with filtering, mixing and data conversion functions) and a digital signal processing unit (the quantity of which depends on the bandwidth to be processed) enables the full reconfigurability of the OBP in-orbit making way to a fully flexible satellite payload.
- The RF Transceivers for SDR have relatively lower bandwidth (200 MHz), whereas wideband (but more power hungry) ADC/DACs (3 GHz bandwidth) can replace them depending on the application. Where needed, these ADC/DACs are good for direct sampling of the RF signal too (up to Ka Band) discarding the need for mixing stages.
- Numerous radiation tolerant alternatives of these digital signal processing platforms are in use in addition to radiation hardened ones.

- Gil Shacham, "On Board Processing Payload"
- Executive Summary Report "Towards the All Optical satellite communications system"

What is coming in the future digital processors?

- Regenerative Processors for Next generation Missions
  - Target Missions: VHTS, UHTS, Mega Constellations
  - Key Features: High throughput, flexibility, user density

- Generic Reconfigurable Processors ("Full" SDR)
  - Target Missions: Low/Medium size missions (also non-telecom)
  - Key Features: modularity, re-usability for several applications, Applications running on custom firmware/software , Reduced time to market

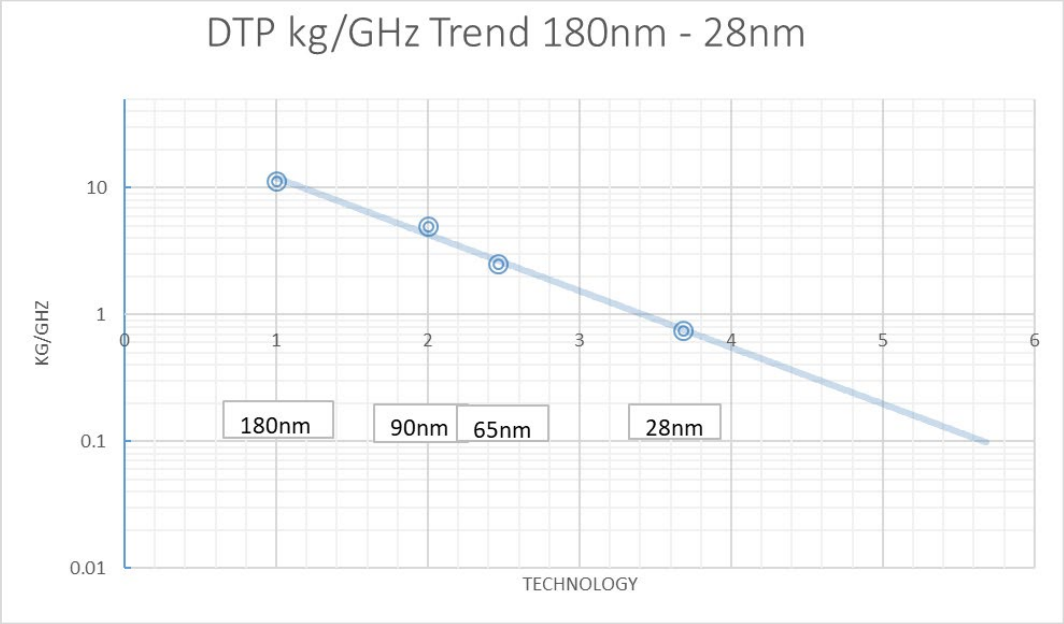
- Increased use of COTS across the different domains

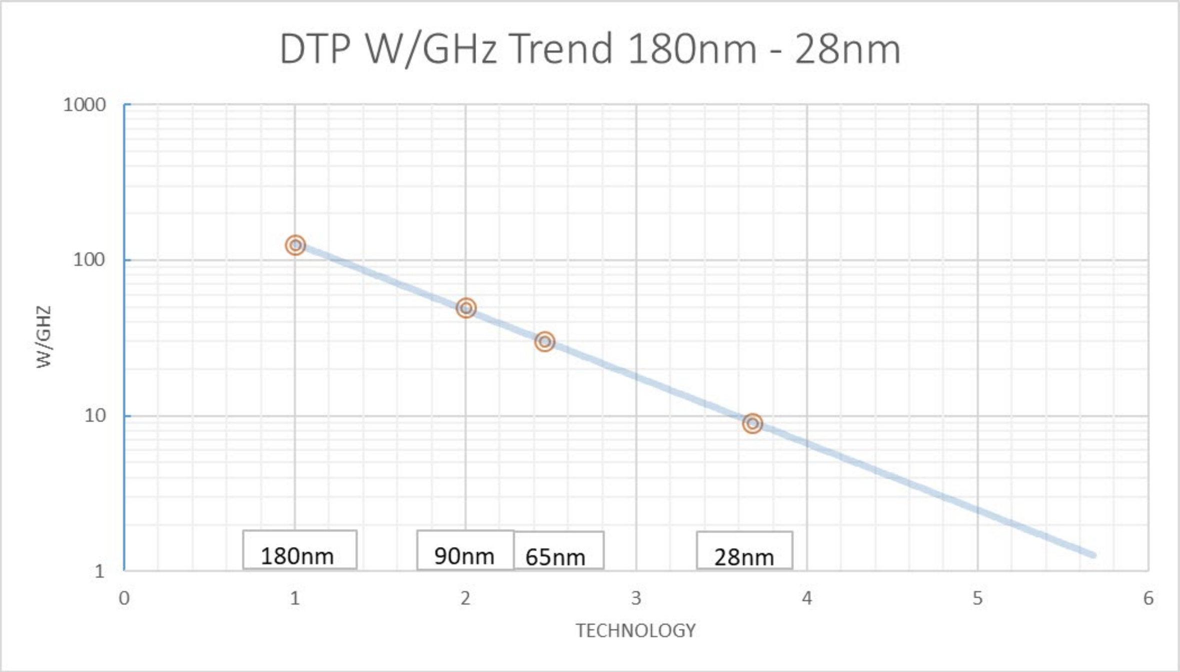
Next Generation of Regenerative Processors

- Regenerative Processors are a key element for GEO and LEO future missions, both commercial or for secure communications. On-going and planned developments e.g. by ADS and TAS in this category, among others.
- Enabling Technologies:
    - UDSM 7nm and beyond
    - Digital Photonics High Speed Serial Links up to 112Gbps
    - High Integration and Heterogeneous Packaging (potentially including PIC)
- Key potential features and functions:
    - Supported throughput >1THz
    - Digital beamforming >500GHz
    - Large number of ports >200
    - Up to 5GHz BW per port
    - Digital IFs (e.g. for ISL), higher RF interfaces e.g. W-band
    - Dynamic spectrum allocation, Jammer cancellation
    - Ethernet Packet Router
    - Possible Inclusion of Optical functions TBC (e.g. Optical WDM interfaces, Optical beamforming)
    - Compatible with 5G/6G standards
- Scaled down versions for LEO constellations

Historical Evolution – from 180nm to 28nm

Historical trend of Mass and Power per GHz of processed bandwidth



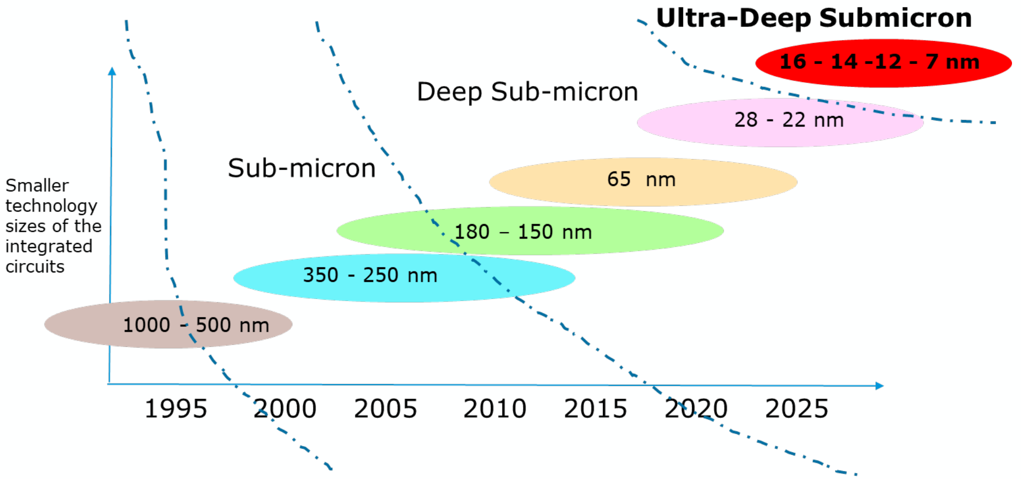


Processor - Ultra Deep Submicron technology

- Highly efficient processors needed for on-board processing and beamforming application, which can only be achieved with Ultra Deep Submicron (UDSM) technology
- Commercial-of-the-Shelf (COTS) processors viable in LEO application with significant cost advantage, but require dedicated radiation mitigation and error handling
  - Mostly non-European solutions
  - Not suited for safety and security sensitive application

=> Develop a UDSM Radiation-Hard Application Specific Integrated Circuit (ASIC) mixed-signal standard cell library and IP portfolio based on 7 nm (or beyond) CMOS technology for the design of complex ASIC

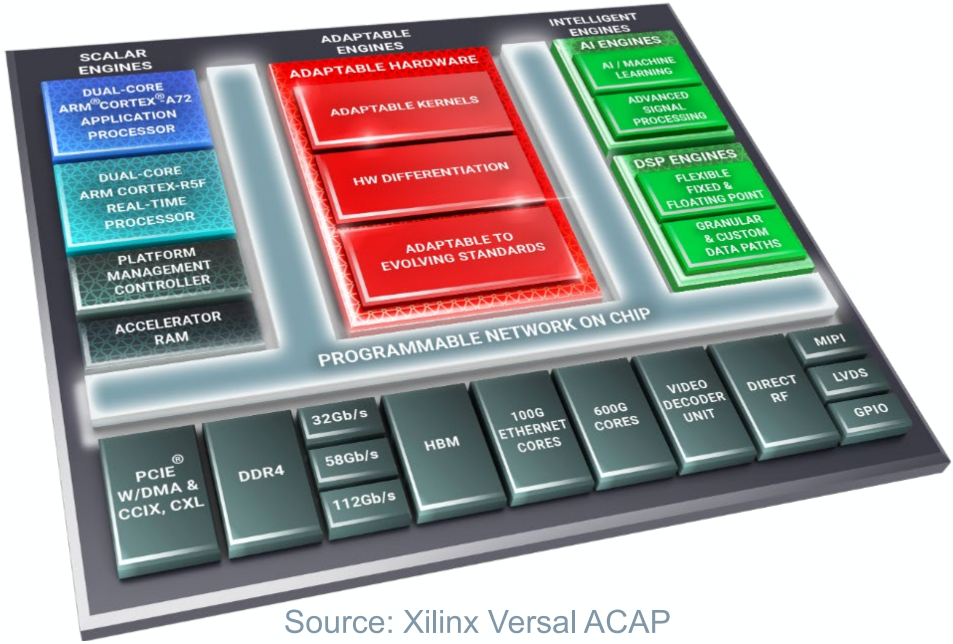
GOAL:
Increase competitiveness for European industry in the telecom sat market, secure/high performance Navigation applications and state of the art Earth Observation payloads to meet future NAV and EO mission challenges.



Processor – RF System-on-Chip (RfSoC)

High integration needs require RF System on Chip providing in a single package European, rad-hard UDSM based

- Reprogrammable **FPGA** (Field Programmable Gate Array) aiming to increase the processing capabilities and functional density by at least x10 compared to state-of-the-art (SOTA) European solutions
- Multi-Core **Microprocessor**, based on open-source RISC-V, increasing the processing capacity by at least x20 compared to the SOTA European solutions
- Multiple **RF** Analog to Digital (**ADC**) and Digital to Analog (**DAC**) converter for direct conversion from/ to Ka band and beyond
- **Accelerators** for Digital Signal Processing (AI, beamforming, …), Encryption (AES), DVB-S2X, ….
- Serializer/ Deserializer (**SerDes**) up to 112 Gbps
- Co-packaged **Optical Transceivers** up to 400 Gbps
- **High Bandwidth Memories,** interface to DDR4/ 5/ GDDR6
- High performance Network-on-Chip (**NoC**)

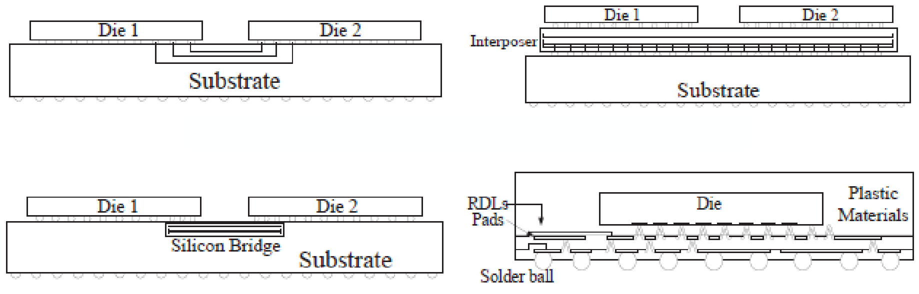


Source: Xilinx Versal ACAP
https://www.xilinx.com/products/silicon-devices/acap/versal.html

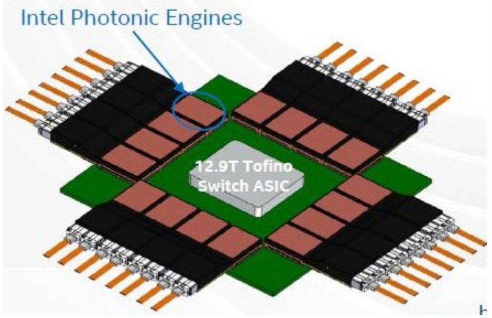
Processor – Packaging Solutions

High integration needs require packaging solutions that allow heterogeneous integration and corresponding interconnection standards/ protocols

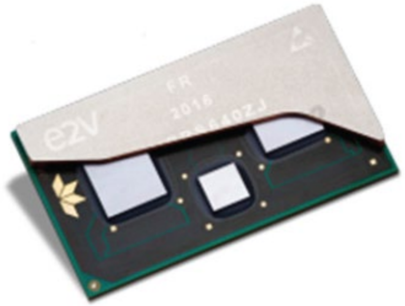
- Substrate-, Silicon Interposer-, Silicon-Bridge- or RDL-based
- Co-packaging of Electro-Optical transceivers
- Move to 2.5D 3D packaging solutions



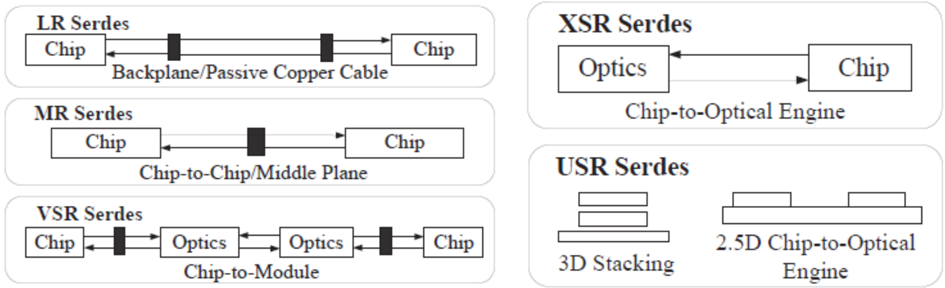
Source: Chiplet Heterogeneous Integration Technology - Status and Challenges
https://www.mdpi.com/2079-9292/9/4/670



Source: Intel Tofino, HotChips 2020



Source: Teledyne e2v
White Paper Advanced System in Package



Source: Chiplet Heterogeneous Integration Technology - Status and Challenges
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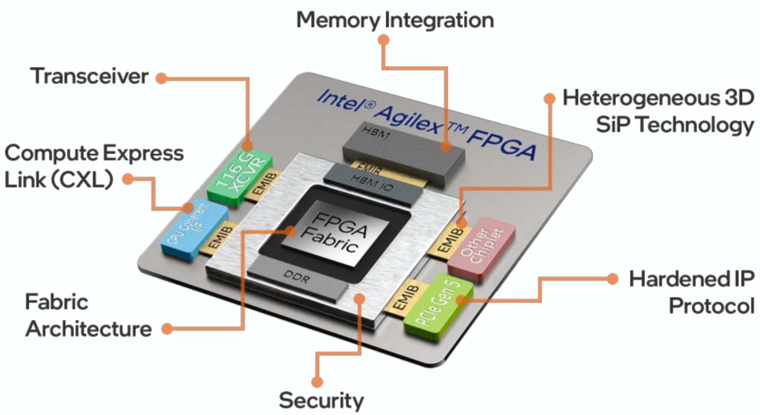
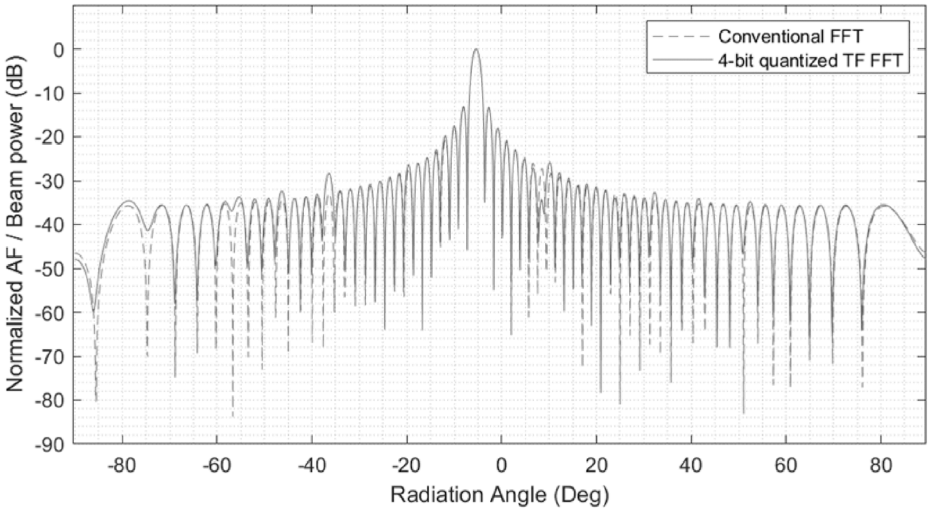


Source: Intel Agilex
https://www.intel.com/content/www/us/en/products/details/fpga/agilex.html

Efficient Digital Signal Processing



Example of Radiation Pattern Comparison between FFTs implementations

Resource estimation for 16×16 2D-FFT

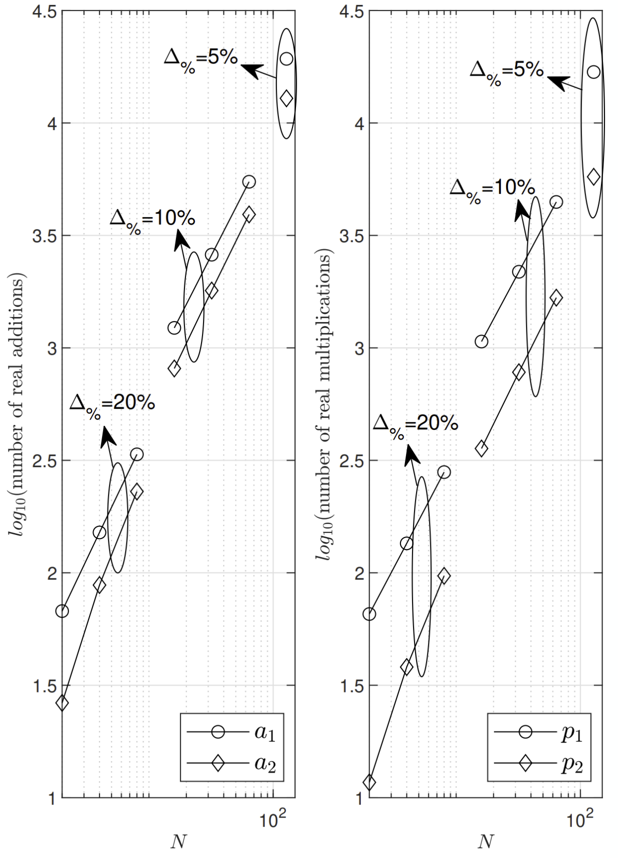
Resources	Power consumption (W)	LUT	FF	DSP
Conventional 2D-FFT	17.531	563680	1241472	6144
Fully unrolled 2D-FFT	8.109	130208	112707	640
4-bit TF quantized 2D-FFT	8.056	142592	112643	0

Power and Area Analysis Xilinx US+ reference FPGA, 16 bit resolution @125MHz

- Development of efficient algorithms and processing techniques are essential to mitigate the complexity and power consumption challenges, associated with the signal processing chains of telecom processors.
- One noteworthy example is the ongoing work undertaken by the University of Luxembourg, TAS-I and SES under an ESA contract.
- The main objective of this activity is to create an efficient digital beamforming technique for satellite scenarios that offers low power consumption and efficient area utilisation through the use of FFT (Fast Fourier Transform).
- The activity involves modelling and testing a fully unrolled FFT implementation for digital beamforming purposes. In this technique, the twiddle factors are designed based on 4-bit quantised values providing a big reduction in the resources needed to deliver FFT operations in comparison to conventional techniques. Further optimizations are made to enhance the maximum operating frequency of the design.
- It's noteworthy that the proposed fully unrolled FFT demonstrates a signal-to-noise ratio (SNR) similar to that of conventional FFT implementations.
- Area (resource utilisation) and power analysis comparison is showing high potential of the proposed technique, with power savings that can go beyond 50% wrt conventional FFT

R. Palisetty, G. Eappen, V. Singh, L. M. G. Socarras, V. N. Ha, J. A. V. Peralvo, J. L. G. Rios, J. C. M. Duncan, W. A. Martins, S. Chatzinotas, B. Ottersten, B. Cortazar†, S. D'Addio, and P. Angeletti "FPGA Implementation of Efficient 2D-FFT Beamforming for On-Board Processing in Satellites"

Efficient Digital Signal Processing (cont.)

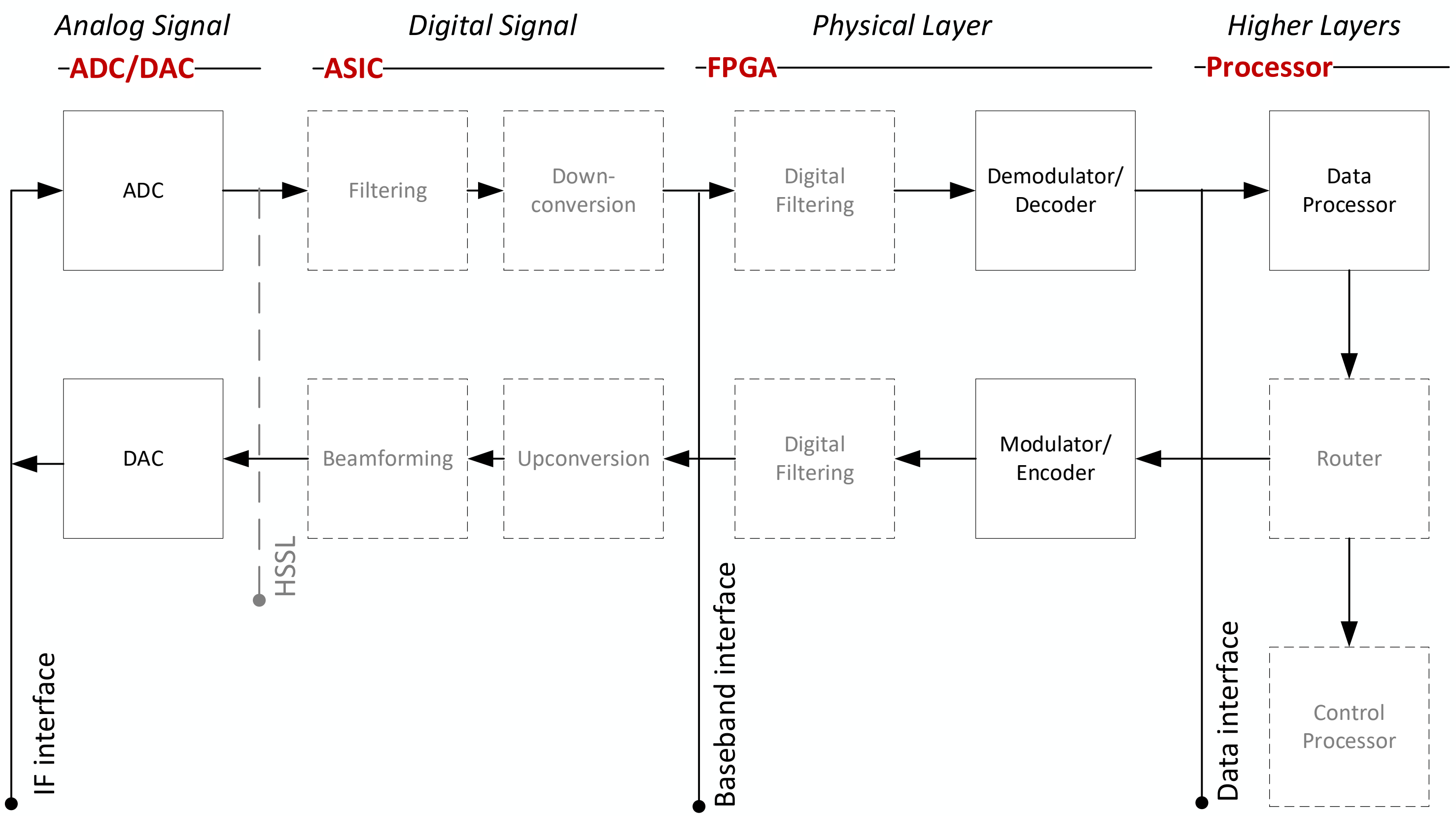


An example to the computational complexity comparison of FFT filter banks using FIR and IIR prototype filter candidates for a specific application within the OBP. The IIR has a big potential to reduce the number of operations wrt conventional filtering techniques.

- Numerous algorithmic and architectural enhancements can be implemented in telecommunication processors to improve the efficiency of signal processing.
- Some key areas are:
  - Multiplierless designs, utilisation of Reconfigurable Multiplier Blocks
  - Design and use of specialised digital filter, datapath and coefficient quantisation tools
  - Critically Sampled/Reduced over-Sampling Channelisation.
  - Reconfigurable and Tunable Filter banks to enhance flexibility in channel width and centre frequency.
  - Improvements in FFT operations through reconfigurable FFT blocks and coefficient store strategies.
  - Designing additional efficient processing components within ASICs to support multiple missions, air interfaces, and customer requirements
  - Compression of the Interconnect Data.
  - Digital beamformers to support non-uniform antenna arrays and non-uniform beam lattices; true-time-delay beamformers.
  - Exploration of alternative filtering and modulation techniques (Almost Linear Phase IIR filters and DCT/DFT)

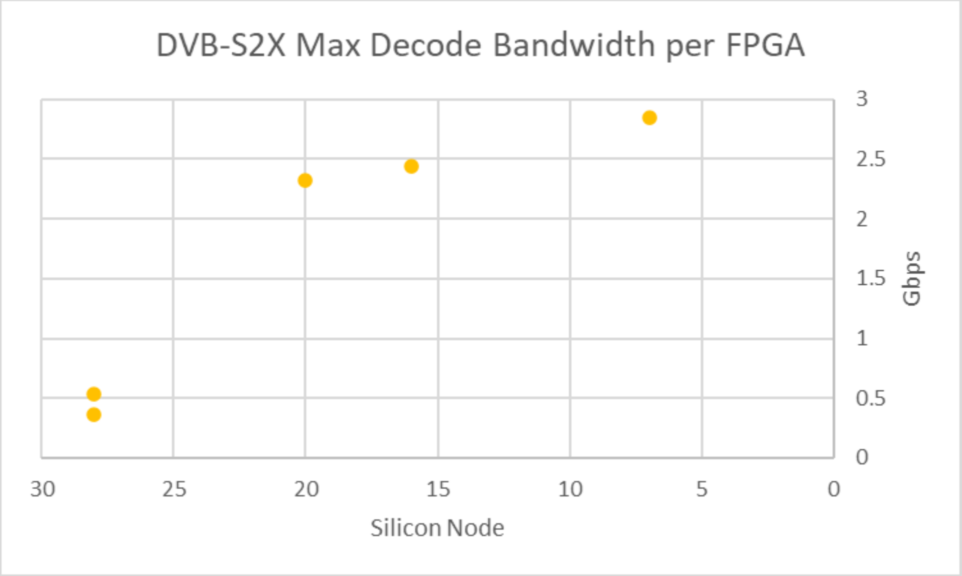
A. Coskun, S. Cetinsel, I. Kale, R. Hughes, P. Angeletti, and C. Ernst, "Digital Prototype Filter Alternatives for Processing Frequency-Stacked Mobile Sub-Bands Deploying a"Single ADC for Beamforming Satellites"
A. Coskun, I. Kale, R.C.S. Morling, R. Hughes, S. Brown, and P. Angeletti, "The Design of Low Complexity Low Power Pipelined ShortLength Winograd Fourier Transforms,"
A. Coskun, I. Kale, R.C.S. Morling, R. Hughes, S. Brown, and P. Angeletti, "Efficient Digital Signal Processing Techniques and Architectures"

SatCom Payload Digital Components



Digital Payload Components

- Mixed signal ASIC RF front-end (> L-band)
  - integrated ADC/DAC
  - Digital/Hybrid Beamforming
- FPGA / SoC communication protocol (> 250 MHz)
  - Flexible or Reconfigurable Decoding/Encoding
  - Flexible or Reconfigurable Modulation
  - DVB-S2/RCS and 5G-NR protocols handling
- SW based packet switching / router (100 Gb)
  - MAC layer handling
- HSSL/SERDES/Ethernet (100Gb)
  - High speed digital interconnects
- …ISL coherent laser digital signal processing



European 7nm is critical for future satcom payload digital processing

Satellite Communication Payloads: an overview of past, present and future trends and challenges – Annex on 5G/6G

Maria Guta
Connectivity & Secure Communications
ARTES SPL 5G/6G
European Space Agency – ESTEC
02/10/2023

Anticipate NTN systems design vs standardisation time

5G — **5G Advanced** — **6G**

2020 Rel. 16

2022 Rel. 17
- Transparent P/L
- NR-NTN direct to smartphones
- NB-IOT
- FR1 (S & L band)

2023 Rel. 18
- Network verified UE location, coverage & mobility
- Backhaul with variable changing delays (ie ISLs)
- Policy/QoS support
- UPF onboard
- Discontinuous coverage
- FR2 mmWave (Ka/Ku-band)

2025 Rel. 19
- Enhancements UL/DL capacity/coverage – Discontinuous coverage
- Regenerative payloads
- IAB/WAB support
- NTN 5GMBS
- NTN RedCap
- NTN/TN Mobility enhancements
- High UE Tx power
- GNSS - enhanced free operations

2026 Rel. 20
- Stage 1: SA1 Services 3D-NTN
- 3D-NTN/Multi-orbit

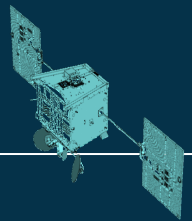
2027+ Rel. 21

SPL Activities on Mid-Term Architectures implementations & NTN Systems & Products developments

SPL Activities on Early definitions of Longer-term NTN Systems Architectures - Roadmaps – CTE prototypes

SPL Activities on Longer-term NTN System & Products developments

Satellite Technologies



Software Defined Flexible Satellite

Mid-Term 2025-2027 Constellations/ Multi-orbit –Early 3D-NTN

- gNB in Space Nodes
- Edge Core Split
- Edge Computing
- AI onboard (application data)
- Store and Forward
- Multi-orbit Architectures and segments design and development
- Routing optimisation (semantic)

Longer Term 2027-2030 Fully Fledged ML-NTN

- Implementation of 'Greener' Concepts and Technology for Regenerative Payloads
- Implementation of smart ML-NTN with Improved Routers in Space Nodes
- AI for NTN edge nodes network management
- Joint Computing & Sensing

Feasibility Analysis (early prototypes of CTE)

Laboratory testbeds

In orbit Experimentation & Demonstration

- Joint computing, communication and storage architectures optimisation
- Design Tools for Processing FPGAs and ASICs
- 'Greener': Analysis and design tools that correlate energy consumption and processing power for regenerative payloads
- New concepts reduce costs of DRA and specific designs for Small LEO satellites

ARTES Strategic Programme Line 5G/6G Relevant Activities

- 5G-IS – 5G Space Infrastructure Study → Medium & longer term designs and technology roadmap 5G-IS | ESA CSC (Extension for automotive)

Partners

- 5GEOSIS : Response to ARTES SPL 5G ITT on "Repurposable as a Payload": 5G Server in Space for Joint Processing and Communications towards Joint Communications and Sensing

- ARTES SPL 5G ITT on "Beyond 5G/6G networking architectures for multi-layered Non-Terrestrial Networks and smart satellites " – Advanced onboard routing for ML-NTN based on semantic routing enhancements – under negotiation


Thank you for your attention !

Overview of European Earth Observation Spaceborne Radars: Past, Present and Future Challenges

Salvatore D'Addio, Ricardo Pinto, Ernesto Imbembo, Marc Zimmermanns, Max Ghiglione
Payload Engineering Section
RF Payloads and Technology Division
Electrical Department, Directorate of Technology, Engineering and Quality
European Space Agency – ESTEC

02/10/2023

Topics

- Intro
- Radar architectures
- SAR applications
- SAR data rates
- Future SAR missions
- Digital Backends for radars
- Cognitive SAR
- Future SAR on-board processing
- RFI

Why Earth Observation?

Back in 1991 ESA's then Director General Jean-Marie Luton wrote in the ESA Bulletin on ERS-1:

It is increasingly apparent that mankind faces a number of potentially very serious problems of an environmental nature, including climatic changes due to the Greenhouse Effect, Ozone depletion etc.

Observation of the Earth from space is one of the keys to achieving a better understanding of the Earth as a system and this is vital if we are to make a comprehensive assessment of the influence of man's activities on the environment.

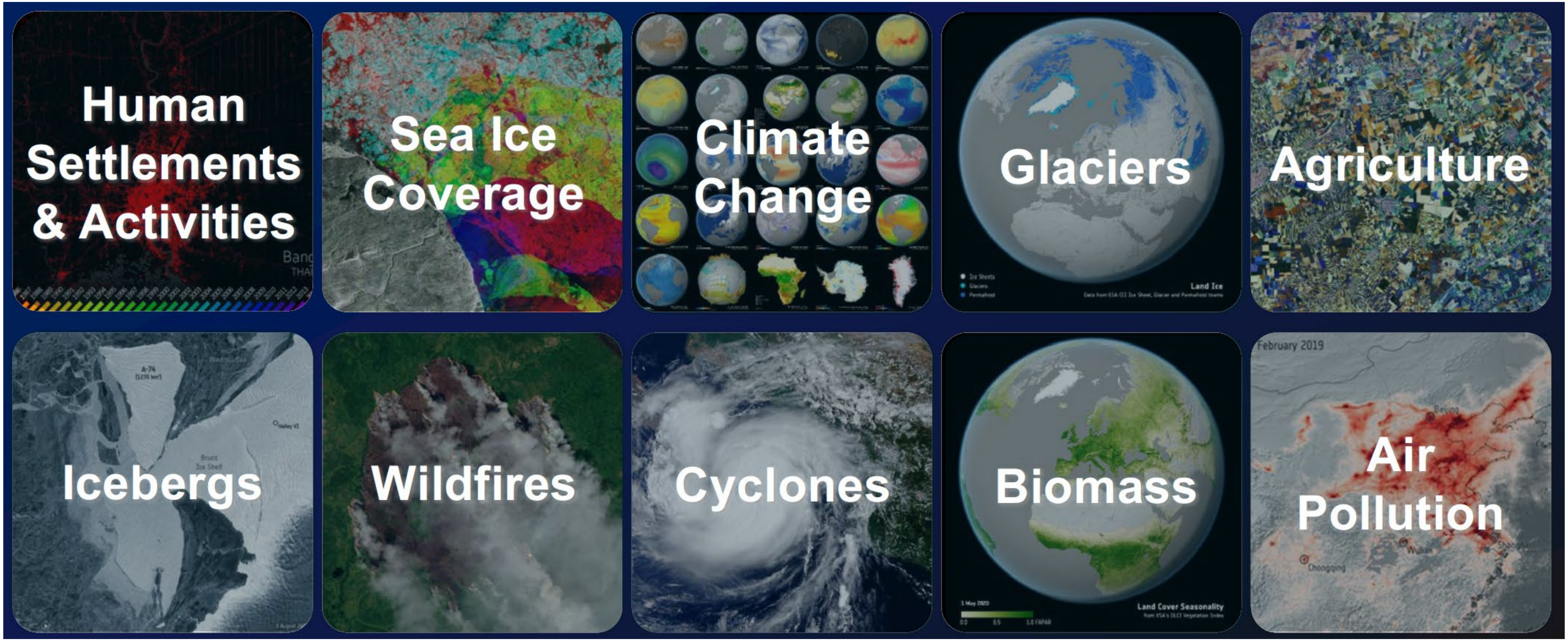
Now, 30+ years on, as evidence grows for anthropogenic climate change and its effects are felt, those words are more valid than ever.

- A key feature of satellite remote sensing is that it can provide consistent global data from a single instrument, avoiding problems of cross-calibration etc.
- There is, however, an inevitable trade-off between spatial and temporal sampling from low Earth orbit.
- <u>New missions and user-needs call for more coverage, better performance, better revisit time, reduced latency, => more DATA!</u>

EO Provides “Big Data” on the entire planet

ESA Operated Missions Today >25TB new data per day, >250TB distributed data

Remote sensing enables the understanding and monitoring of earth processes and human activity



Devising Earth Observation Missions

esa

Living Planet Program

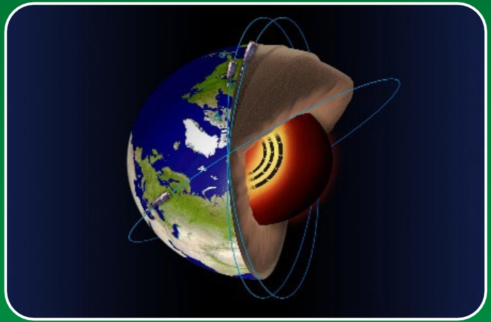
Research Missions

Member States

Earth Explorers

& Scouts

Ideas from science partners in MS (Open Calls)



Also Mission of Opportunity with partners outside MS (NGGM with NASA)

Earth Watch Missions

Copernicus

EUMETSAT

Meteorology

InCubed

in³

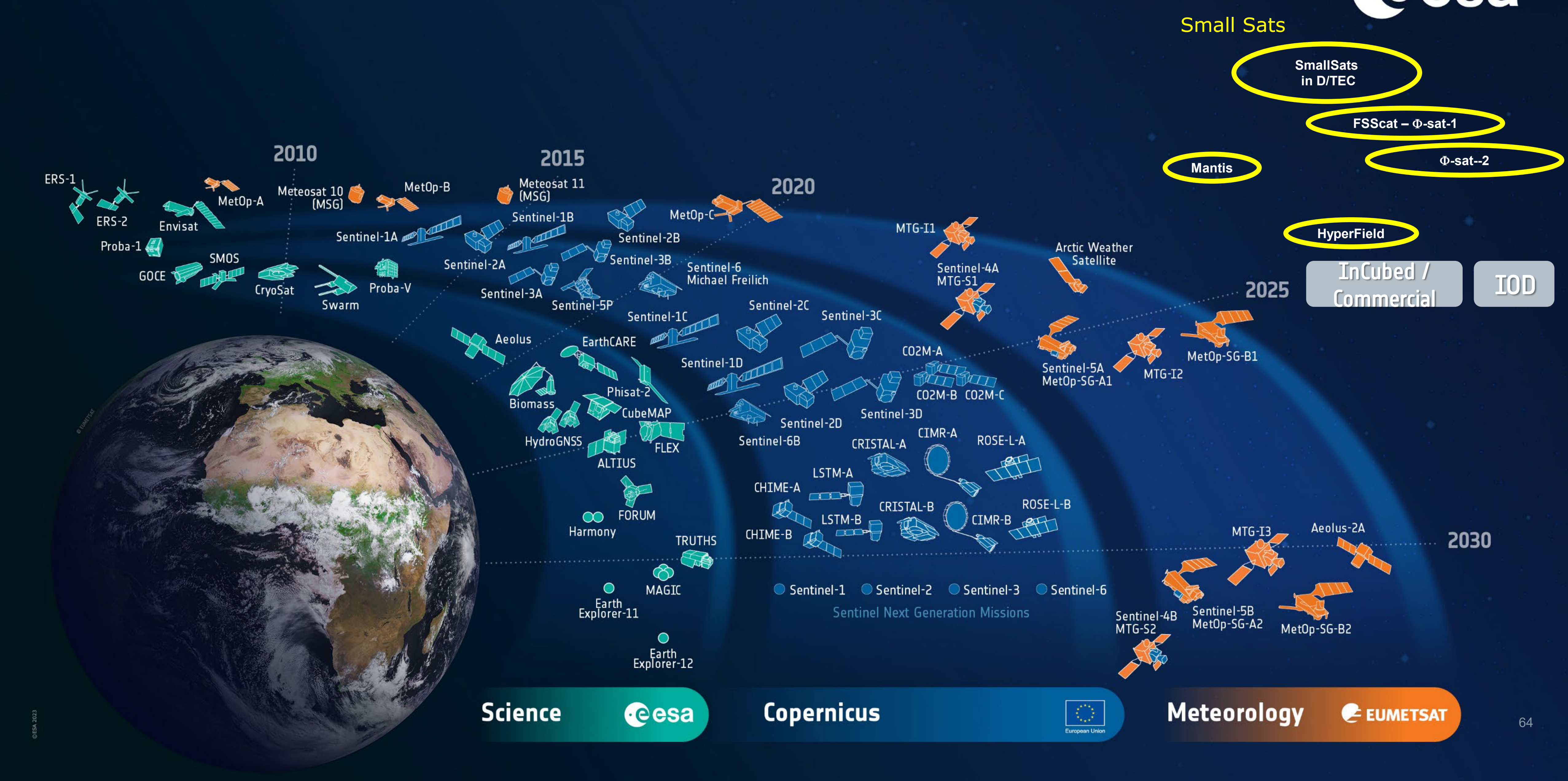
Member States

Other

Altius
TRUTHS
Artic Weather Sat
PNRR

- User needs from institutional partners & industry

ESA Developed Earth Observation Missions



esa

EO data

address

almost all parameters

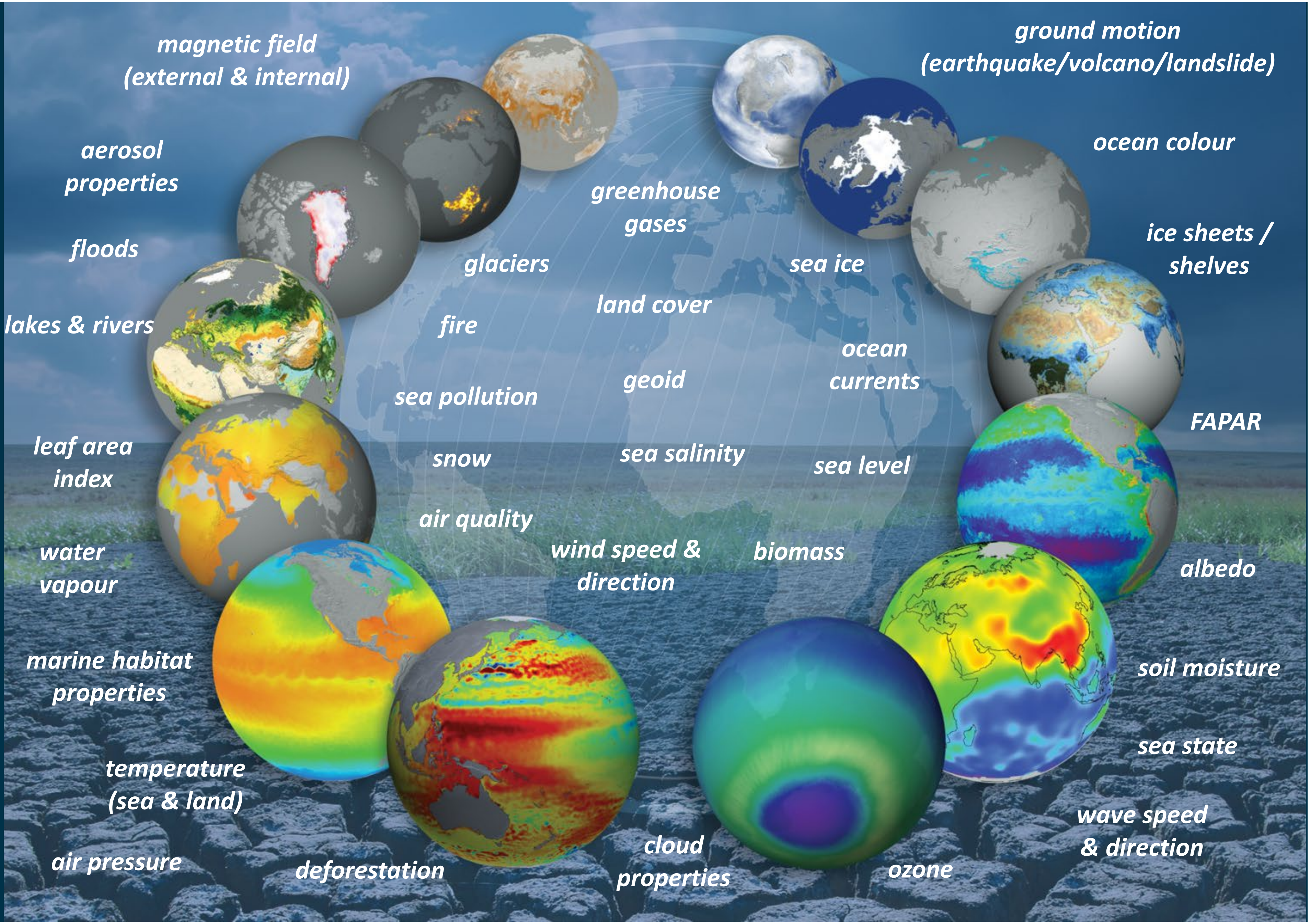
retrievable

from space

→ extreme diversity

of data, applications,

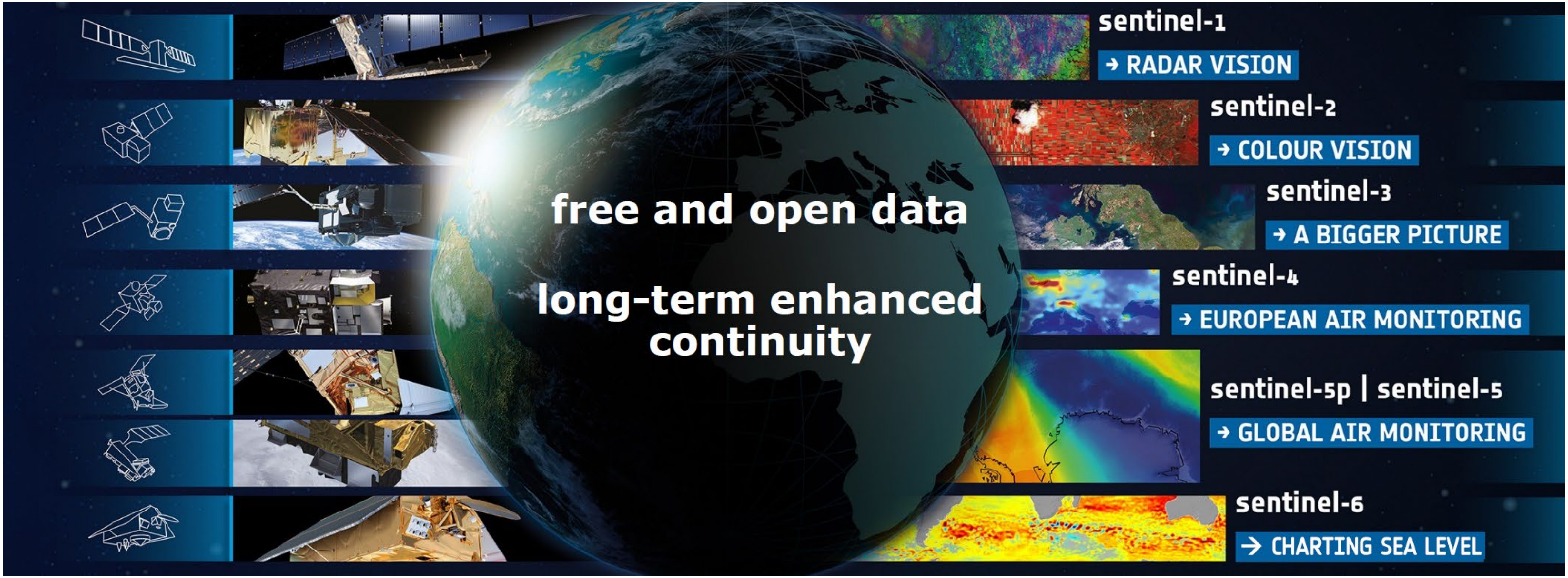
users



Copernicus Sentinels – First generation

European Commission and ESA Program

Global Monitoring for environment and security



New Sentinels to answer evolving user needs

Why Microwaves?

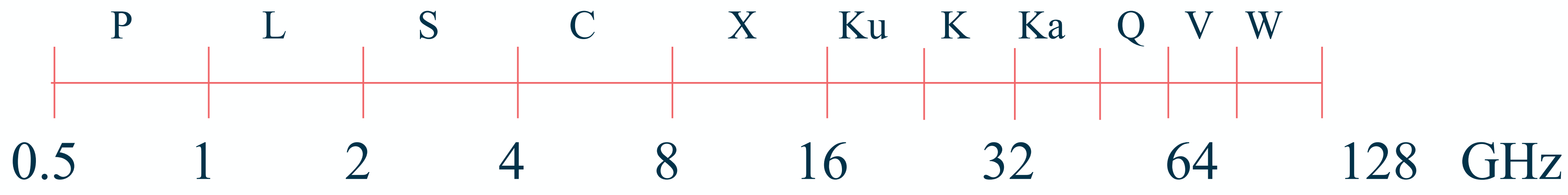
Factors affecting the choice of frequency are:

- ✓ITU frequency allocation – especially for wideband radars
- ✓Antenna size – hence beamwidth and gain
- ✓Propagation effects
- ✓Ambiguities (range, Doppler)
- ✓Technology Readiness and Availability of microwave components (HPAs, Antennas, Digital Functions, etc.)

Frequency band	Frequency range	Type of Application
VHF	300 KHz - 300 MHz	Foliage/Ground penetration, biomass
P-Band	300 MHz - 1 GHz	biomass, soil moisture, penetration
L-Band	1 GHz - 2 GHz	agriculture, forestry, soil moisture
C-Band	4 GHz - 8 GHz	ocean, land, agriculture
X-Band	8 GHz - 12 GHz	agriculture, ocean, high resolution radar
Ku-Band	14 GHz - 18 GHz	glaciology (snow cover mapping), land, ocean,
Ka-Band	27 GHz - 47 GHz	high resolution radars, snow/ice, ocean

ITU BW allocations for EO radars

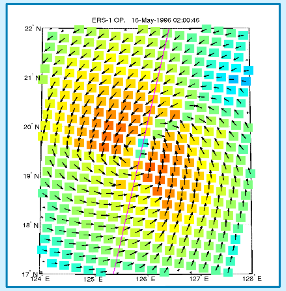
- P-band – 6MHz
- L-band – 85MHz
- S-band – 150MHz
- C-band – 320MHz
- X-band – 600MHz
- Ku-band – 500MHz
- Ka-band – 500MHz

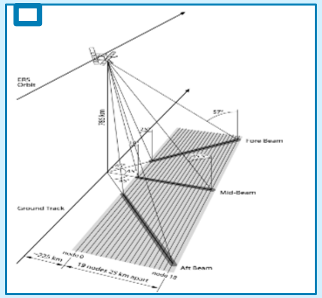


Main Spaceborne Radars Types

Among various applications, the most employed microwave active instruments for earth observation remote sensing are:

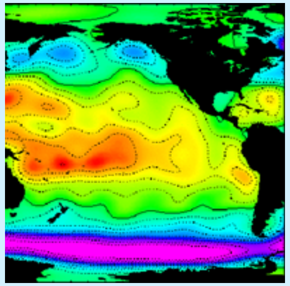
Scatterometers (Wind speed)

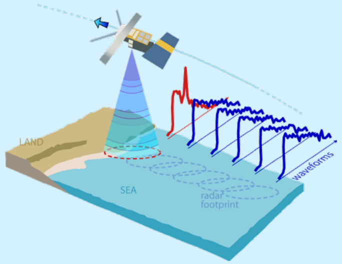




- ocean surface wind vectors for use primarily in weather forecasting and climate research
- soil surface layer, surface roughness, and vegetation
- sea ice extent, permafrost boundary, desertification

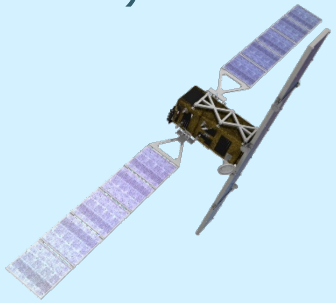
Altimeters (Sea Surface Anomaly)





- Ocean and Coast (Ocean Waves , Ocean Currents and Topography, SWH)
- Land (Topography/Mapping)
- Snow and Ice (Sea Ice)
- Atmosphere (Winds)

Synthetic Aperture Radars (Imaging Applications)

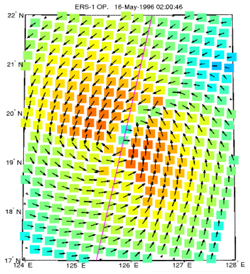


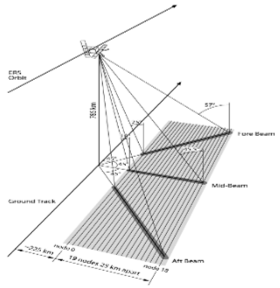
- biomass estimation
- monitoring sea-ice zones and the polar environment
- mapping in support of humanitarian aid in crisis situations
- surveillance of marine environments
- monitoring land surface motion risks
- mapping of land surfaces: forest, water and soil, agriculture

Main Spaceborne Radars Types

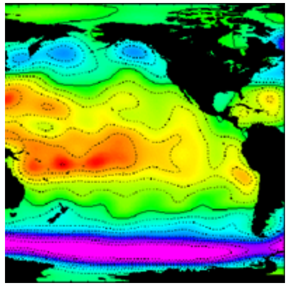
Among various applications, the most employed microwave active instruments for earth observation remote sensing are:

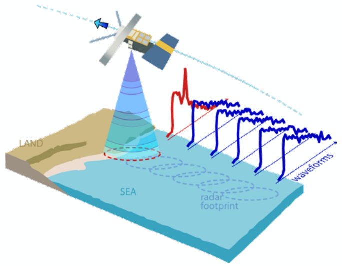
Scatterometers
(Wind speed)





Altimeters
(Sea Surface Height)





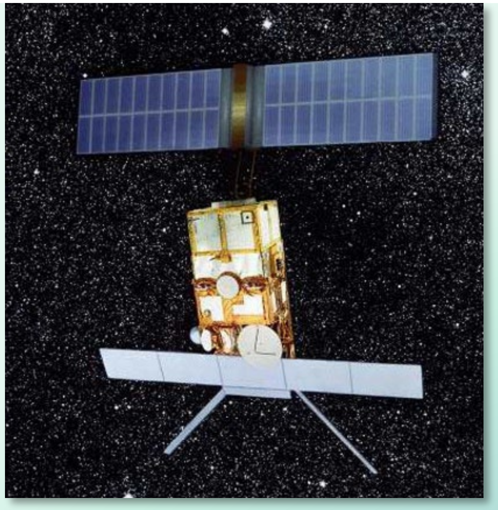
Synthetic Aperture Radars
(Imaging Applications)

Radar Architectures differentiate mainly due to the following aspects/constraints

- the type of acquisition mode/geometry (e.g. nadir looking/side looking)
- the type of parameter of interest (that strictly depends on the application)
- the level of the desired performance (e.g. Swath size/resolution, radiometric accuracy)

These three factors strongly influence the features of the technology needed for each of the radar type and the their development trends

30+ years of C-band SARs developments in Europe



ERS-1 -2 1991/1994

- No Phased Array
- Single Pol
- Single Amplification
- Antenna Size: 10mx1m
- BW: 15MHz
- Resolution: 26x30m (rg-az)
- Swath Width: 100km
- No scanning in Elevation

Envisat 2002

- Phased Array
- Dual Pol
- 320 T/R Modules - 10W
- Antenna Size: 10mx1.3m
- BW: 16MHz
- Resolution: 28x28m - 150x150m (rg-az)
- Swath Width: 100km-400km
- ScanSAR possible

Sentinel-1 2014/2016

- Phased Array
- Dual Pol
- 560 T/R Modules – 16W
- Antenna Size: 12.3mx0.84m
- BW: up to 100MHz
- Resolution: 5x5 – 5x20 - 20x40m (rg-az)
- Swath Width: 80km-250km - 400km
- ScanSAR/TOPS possible

Examples of SARs with Active Antennas

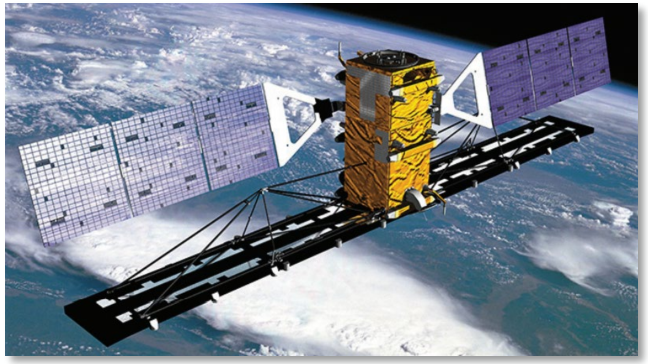
L-band

ALOS-2

ROSE-L

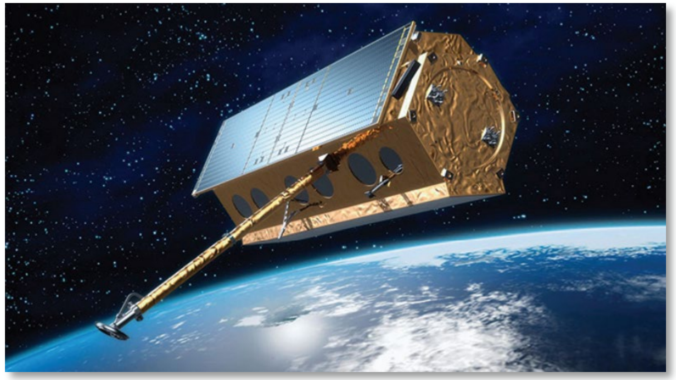
C-band

Sentinel-1



RadarSat-2

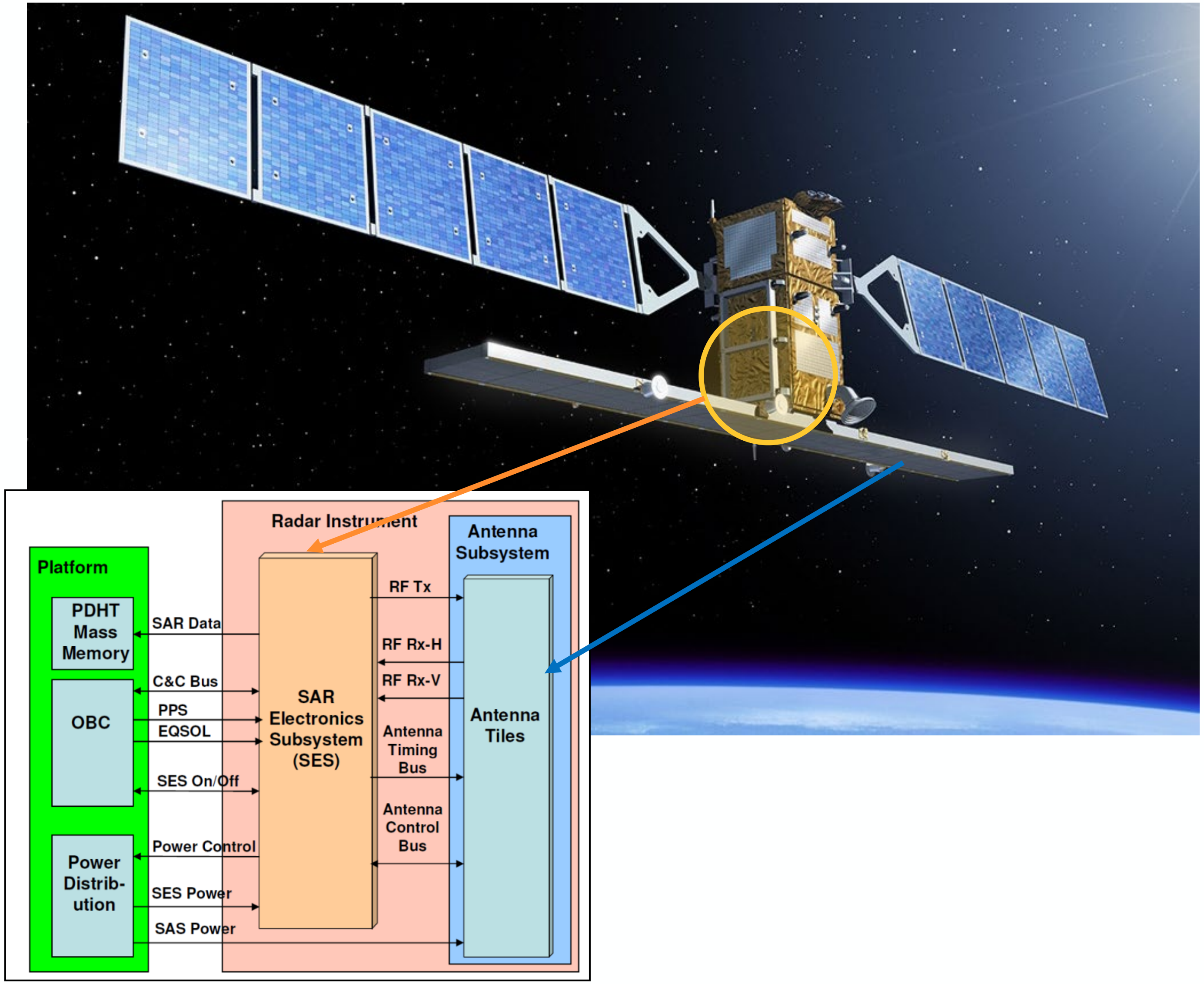
X-band



TerraSAR-X

Cosmo-Skymed SG

Typical SAR Architecture – Sentinel-1 Example



From analysis of the mode requirements the instrument has to support:

-Fast beam scanning at least in elevation direction is needed

=>Multi-beam reflector based SAR or

=>Active array antenna SAR

Considering in addition the following points:

-Fast beam scanning in azimuth is required for TOPS mode

-Wide scan range in elevation requires long focal length for reflector

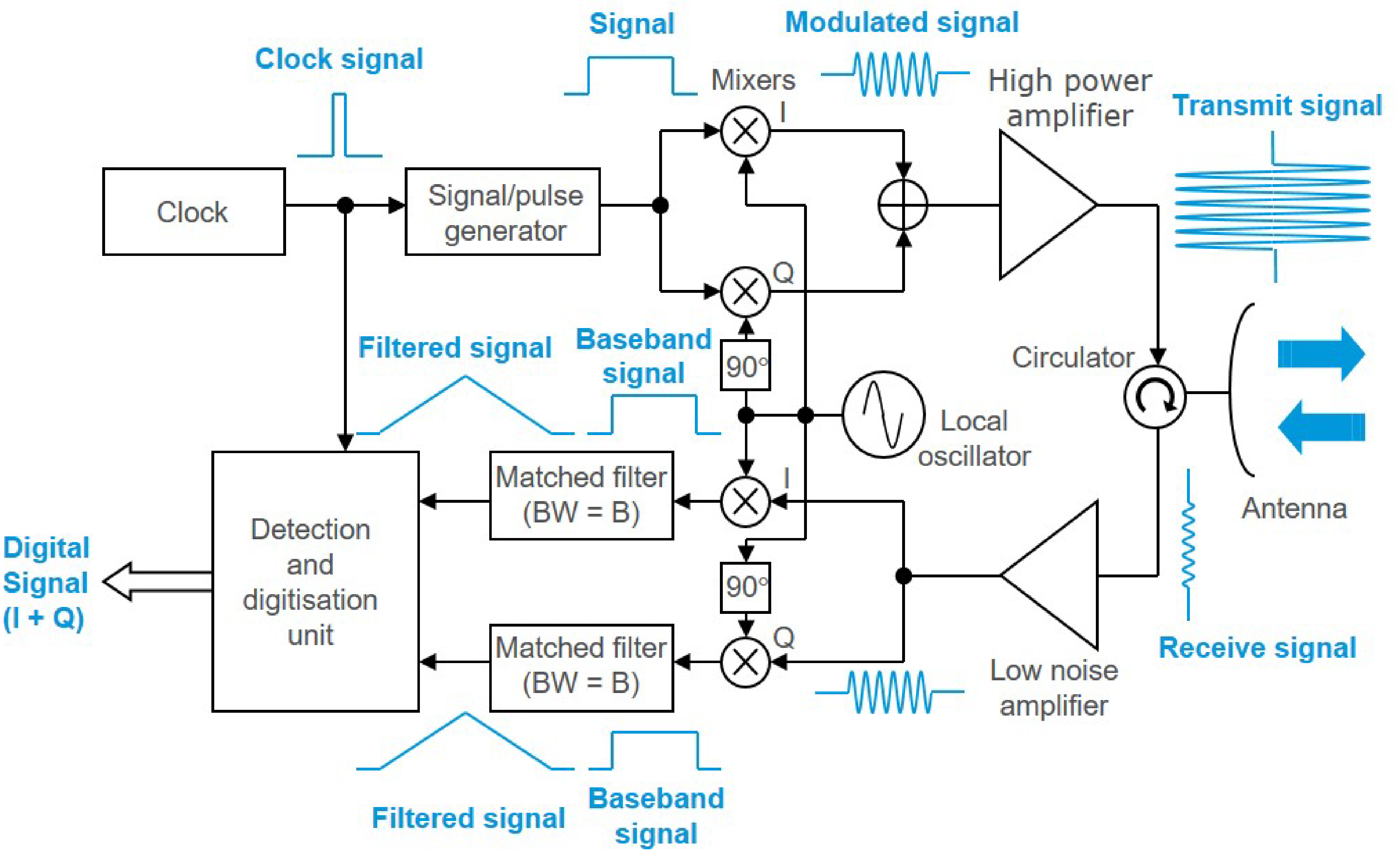
-Design experience from ASAR on EnviSat

⇒**Active Phased Array Antenna**

Typical Radar block diagram

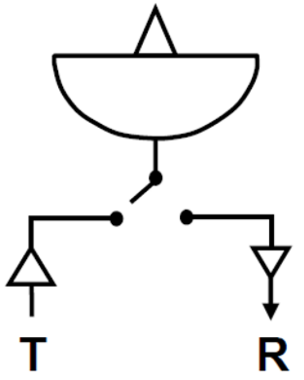
Radar contains:

- **Clock** for time counting;
- **Signal/pulse generator**;
- **Local oscillator** to generate carrier frequ
- **Mixers** for up-conversion (modulation);
- **High power amplifier** (HPA);
- **Circulator** for signal diplexing;
- **Antenna**(s);
- **Low noise amplifier** (+ additional amplifiers);
- **Mixers** for down-conversion (de-modulation);
- **Matched filters**;
- **Detection, sampling and digitization u**
- **Power conditioner** (not shown);
- **Instrument control unit** (not shown).



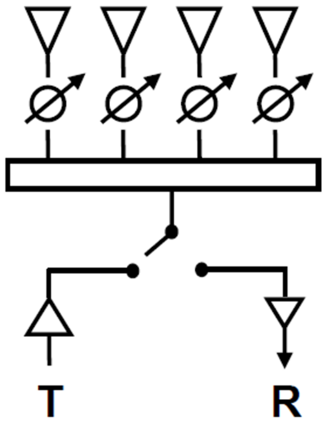
Radar Architecture Overview

Single HPA + Reflector Antenna



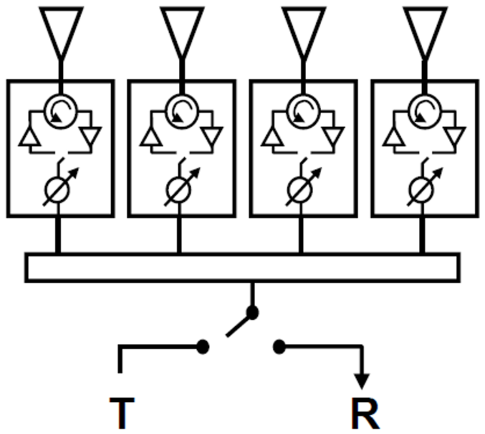
- Simplicity/ Low Cost
- Might require high power per HPA
- Potentially high loss after HPA
- Slow-scan rate /mechanically
- Need redundancy

Single HPA + Phased Array



- Allows shaped beams
- Allows beam scanning
- Might require high power per HPA
- Potentially high loss after HPA
- Need redundancy
- High power analog beamforming

Active Phased Array Antenna

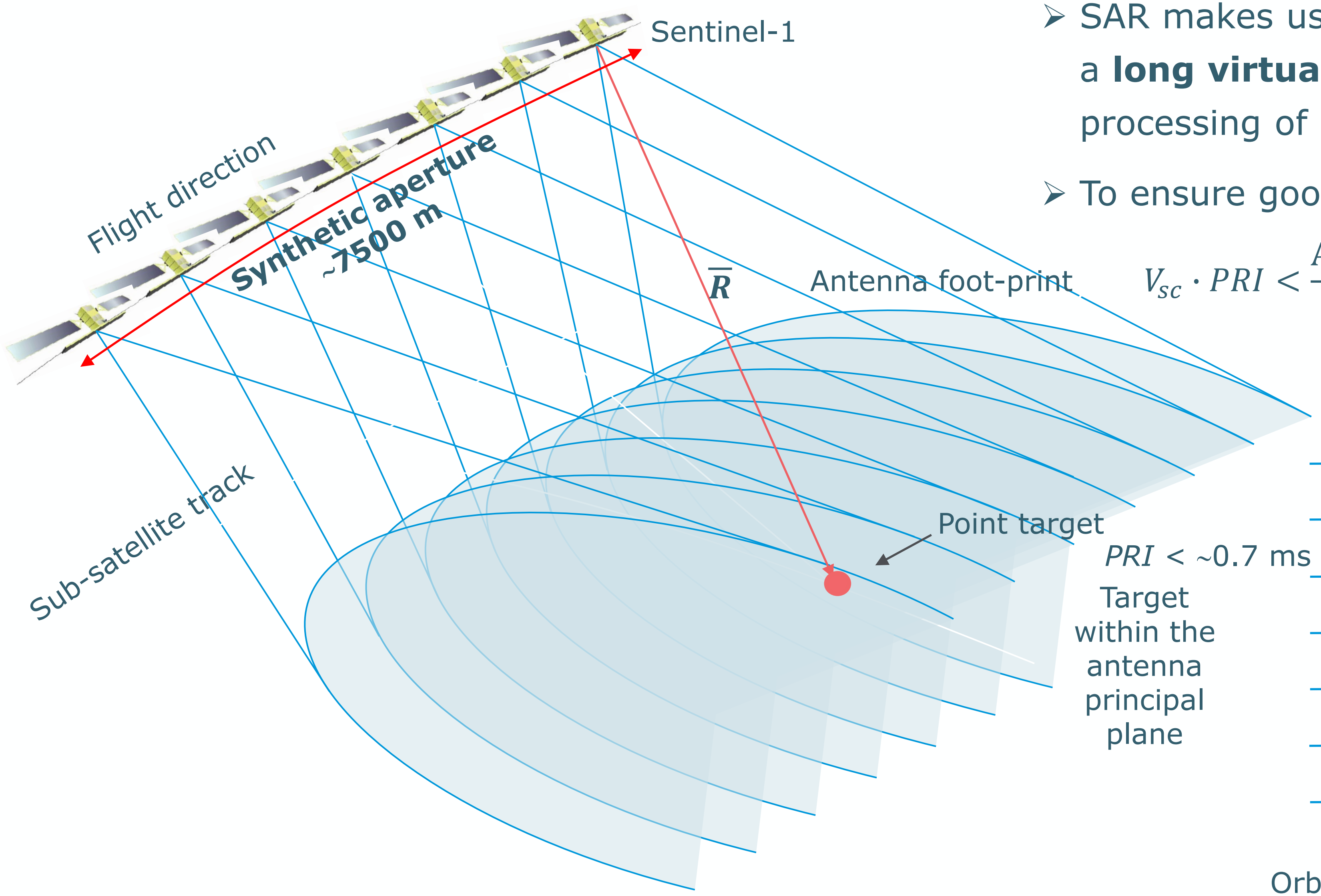


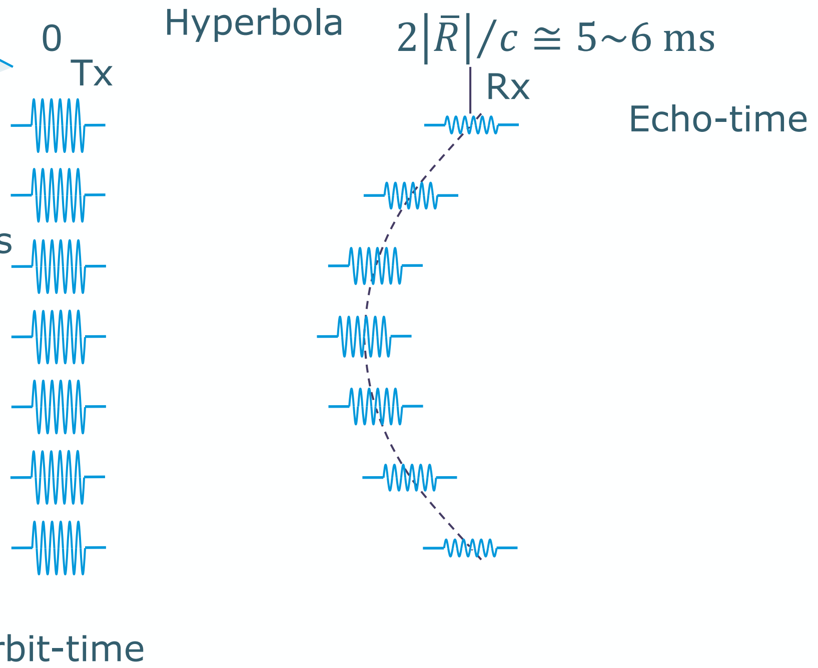
- Allows shaped beams
- Allows beam scanning /flexibility
- Low post-HPA loss
- Graceful degradation
- Low power per HPA
- Complexity/Cost
- Thermal management

Synthetic Aperture Radars – An introduction

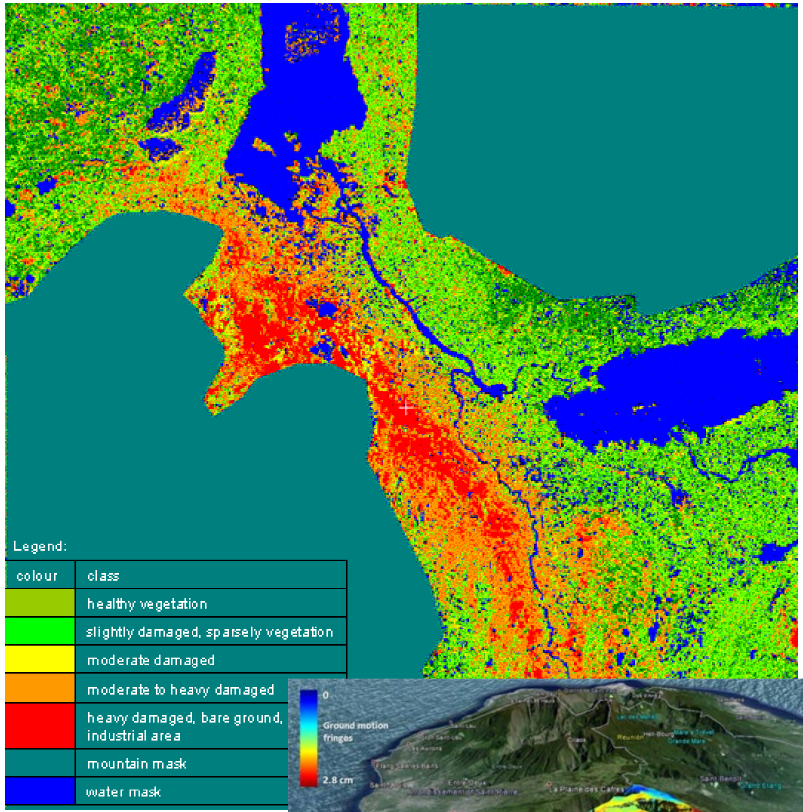
- SAR makes use of the platform motion to synthesize a **long virtual antenna** through the coherent processing of a large number of echo-profiles.
- To ensure good coherence, one needs to satisfy:

$$V_{sc} \cdot PRI < \frac{\text{Antenna length in azimuth (flight direction)}}{2}$$



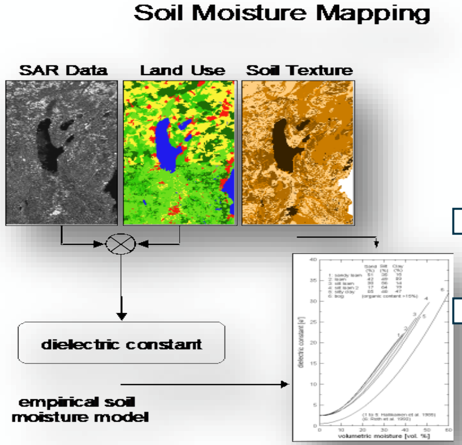


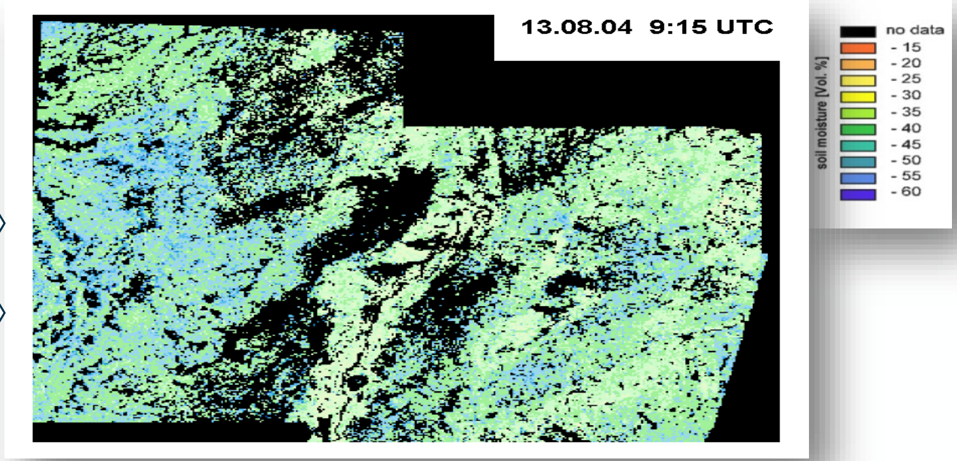
SAR Applications (Land and Maritime monitoring)



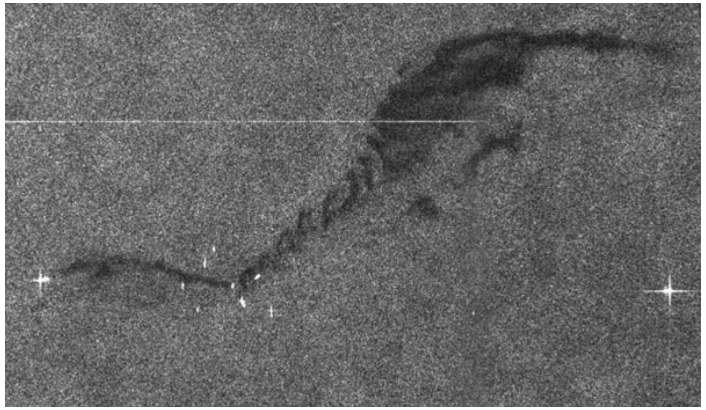
Mapping Deforestation

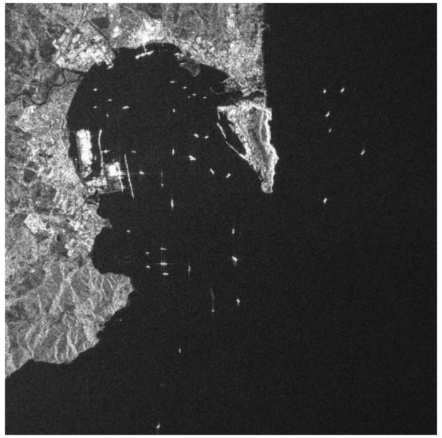
Soil Moisture Inversion





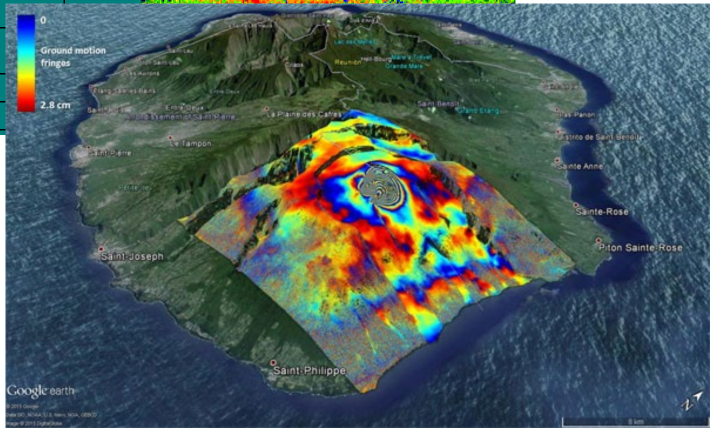
Oil Spill





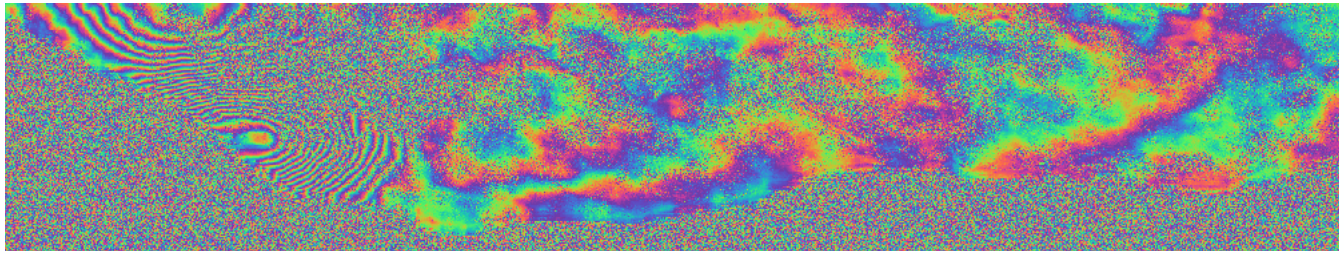
Ship Monitoring

Change Detection

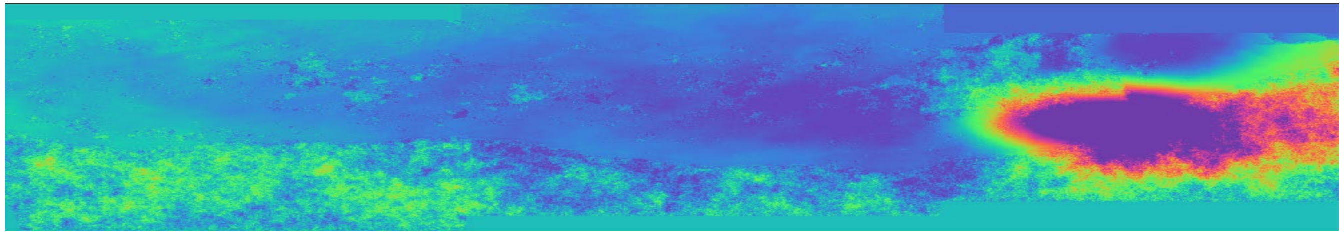


S1 SAR Applications: Interferometry

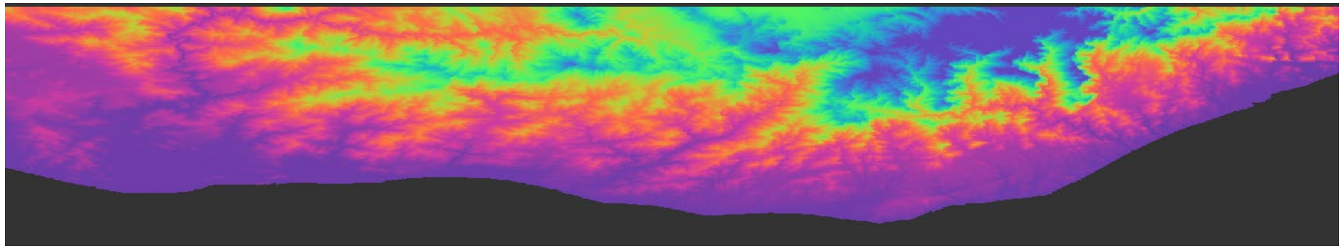
Wrapped Phase



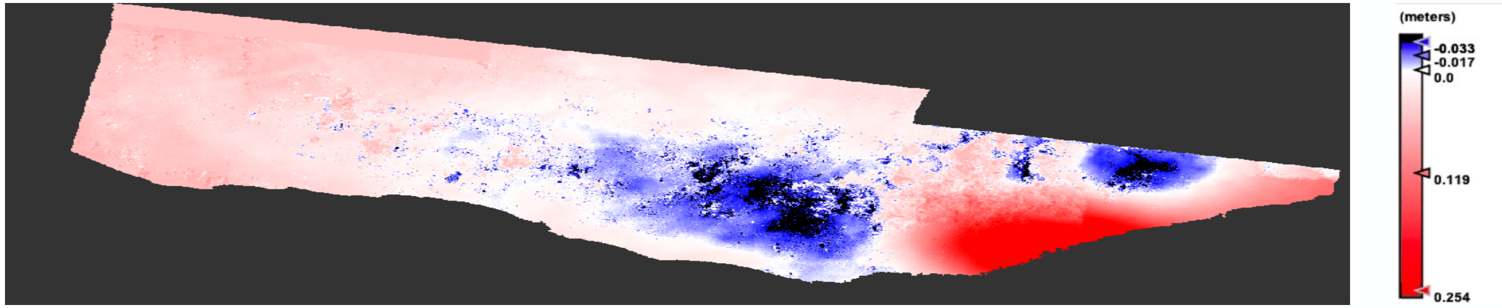
Unwrapped phase



Topographic Phase



Displacement



Images acquired with Sentinel-1

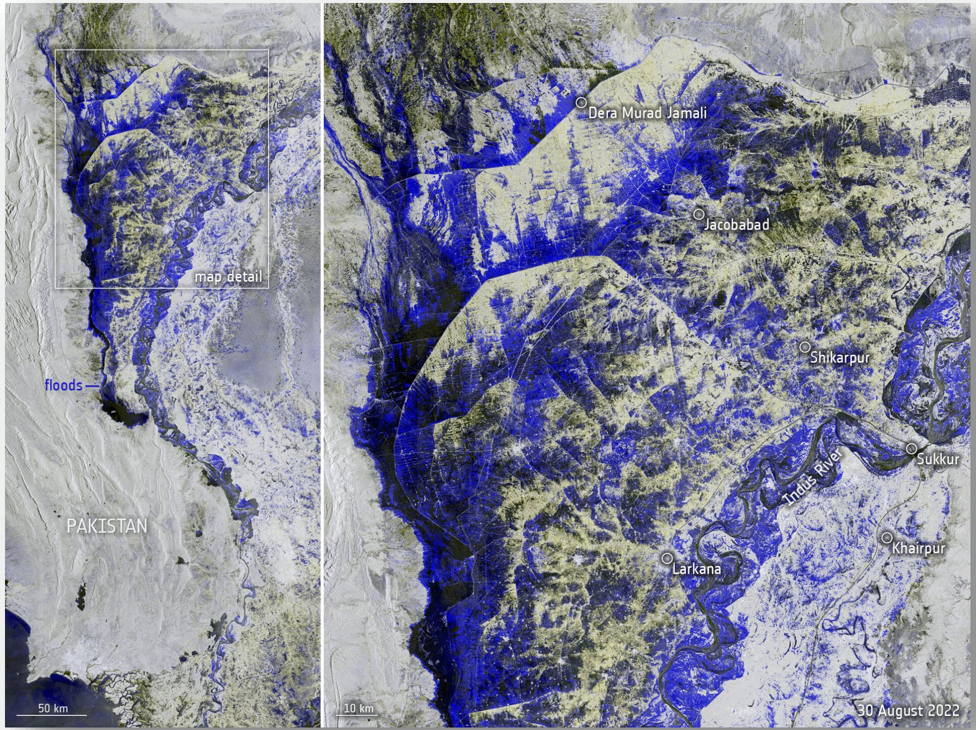
Oaxaca Earthquake
A magnitude 7.4 Mw Earthquake happened in the Mexican State of Oaxaca at 10:29 ET on the 23rd June 2020.

Blue: away from the satellite
Red: towards the satellite

S1 SAR Applications Examples

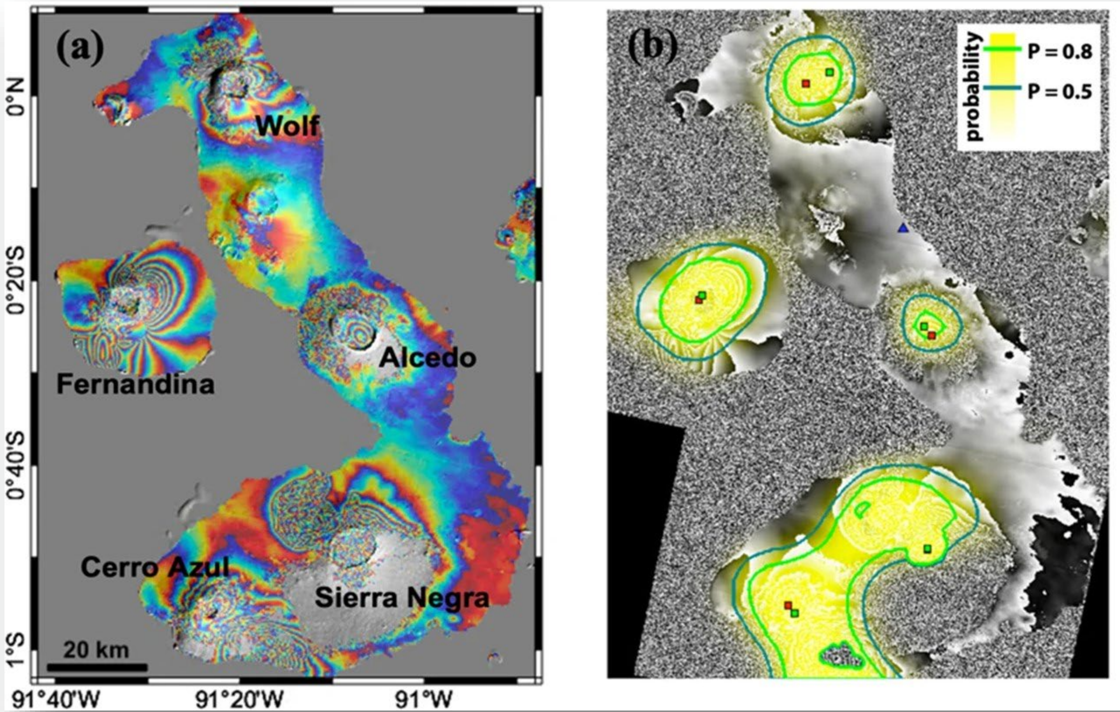
Example of Sentinel-1 SAR data on assessing flooding affecting Pakistan in 2022
Flood map generated thanks to sentinel-1A Data

Heavy monsoon rainfall 9 10 time heavier than usual – has led to a large part of the country being underwater, affecting millions of people in Pakistan



Example of Sentinel-1 SAR data processed to map and predict (through AI/ML) volcanic eruption activity
Galapagos Volcanoes

The graphic on the left shows cumulative displacement between November 2015 and November 2020.
The graphic on the right shows the detection probability generated by the machine learning algorithm.

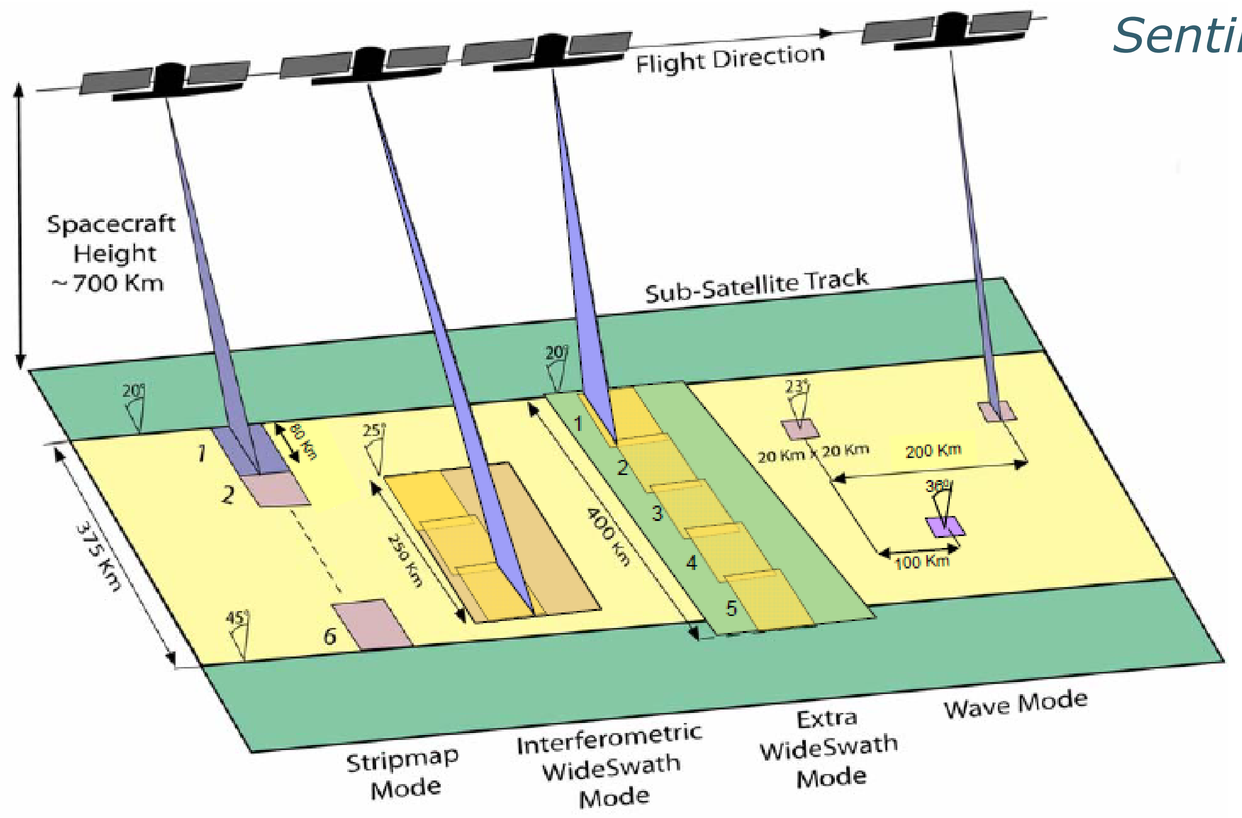


Synthetic Aperture Radar Acquisition Modes

Typical SAR acquisition modes:

- Stripmap
- ScanSAR
- SpotLight
- TopSAR
- ..and several others..!

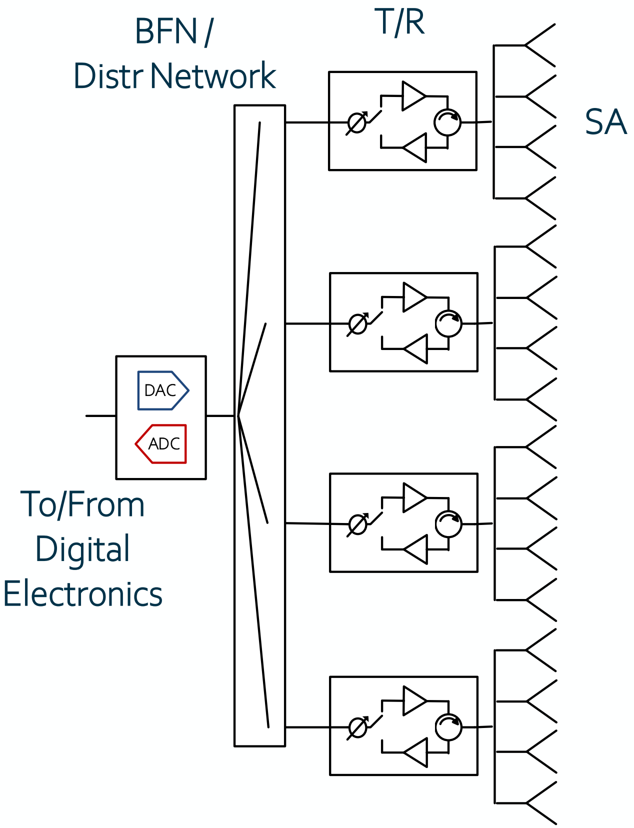
Sentinel -1 Modes



Each mode satisfies different needs , depending on the type of application

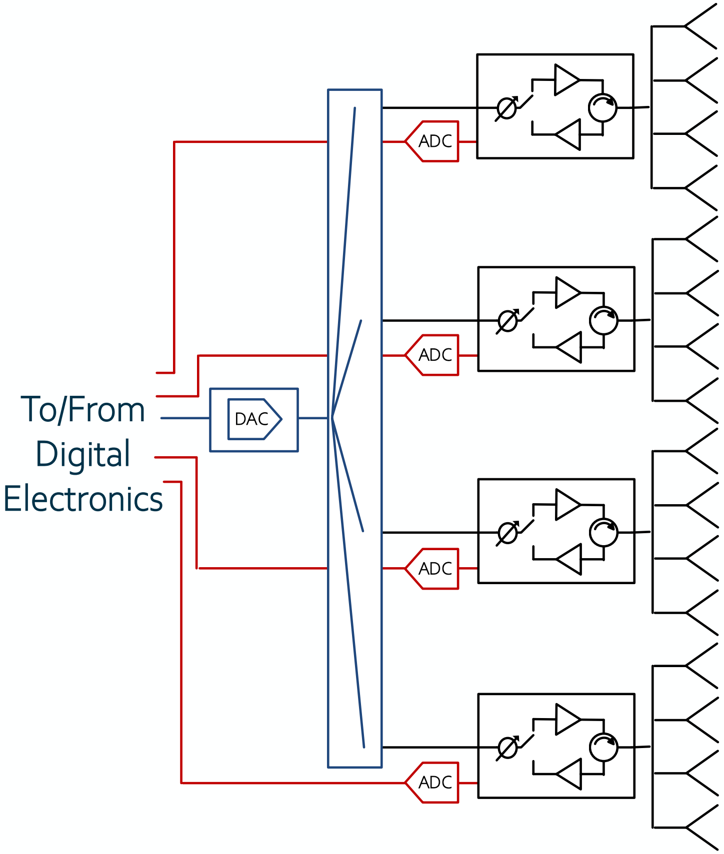
Radar Architectures based on Active Antennas

Fully Analog



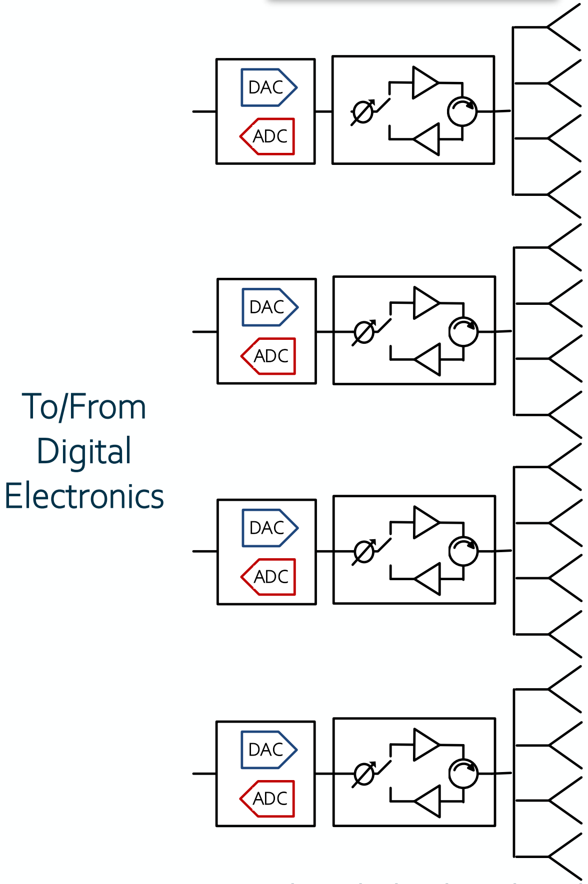
Typical Legacy Spaceborne Radars (e.g. Sentinel-1)

Tx Analog – Rx Digital



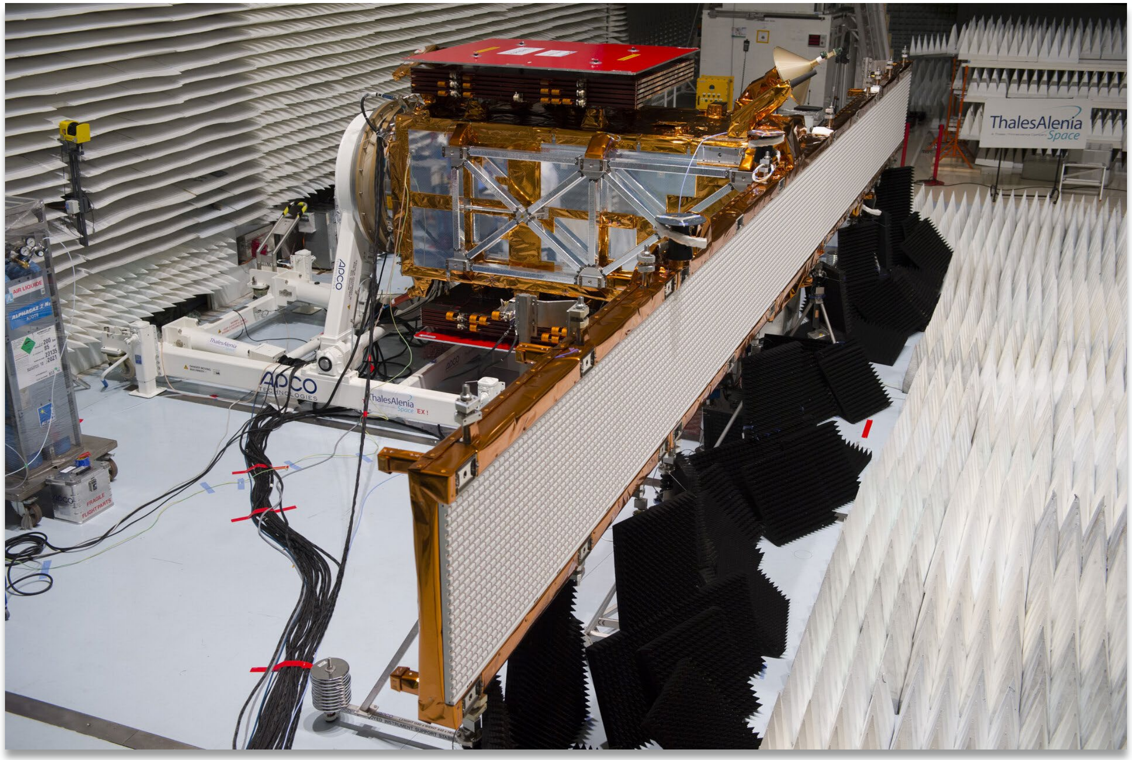
Other typical configuration employ separate Tx/Rx apertures
(e.g. Tx wide beam and many Rx narrow beams)

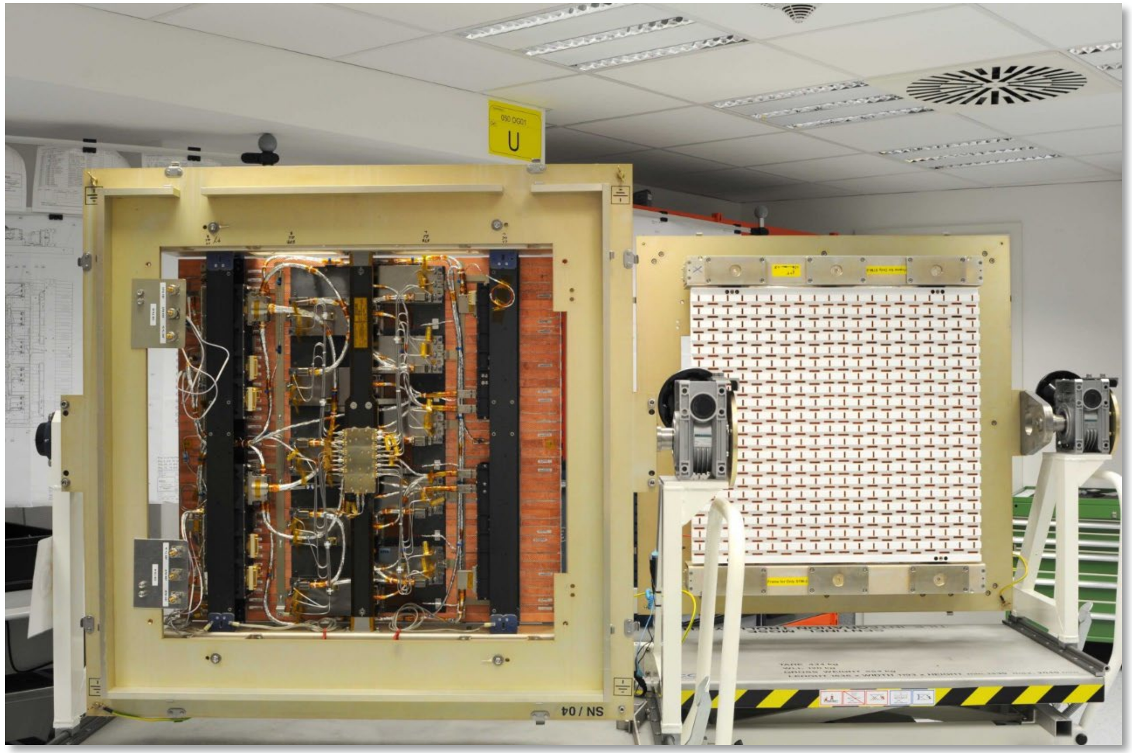
Fully Digital



Intermediate hybrid analog/digital beamforming configurations are often employed

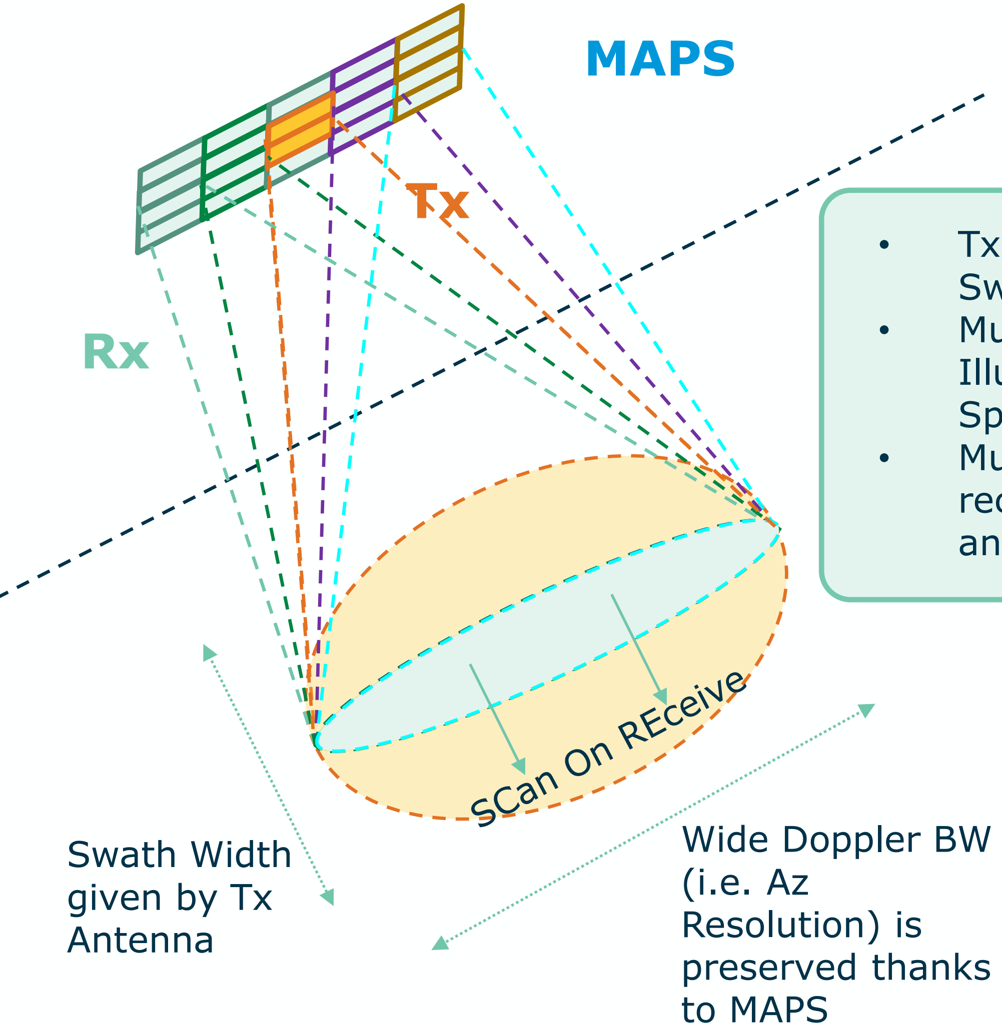
Sentinel-1 Architecture : Tile Example



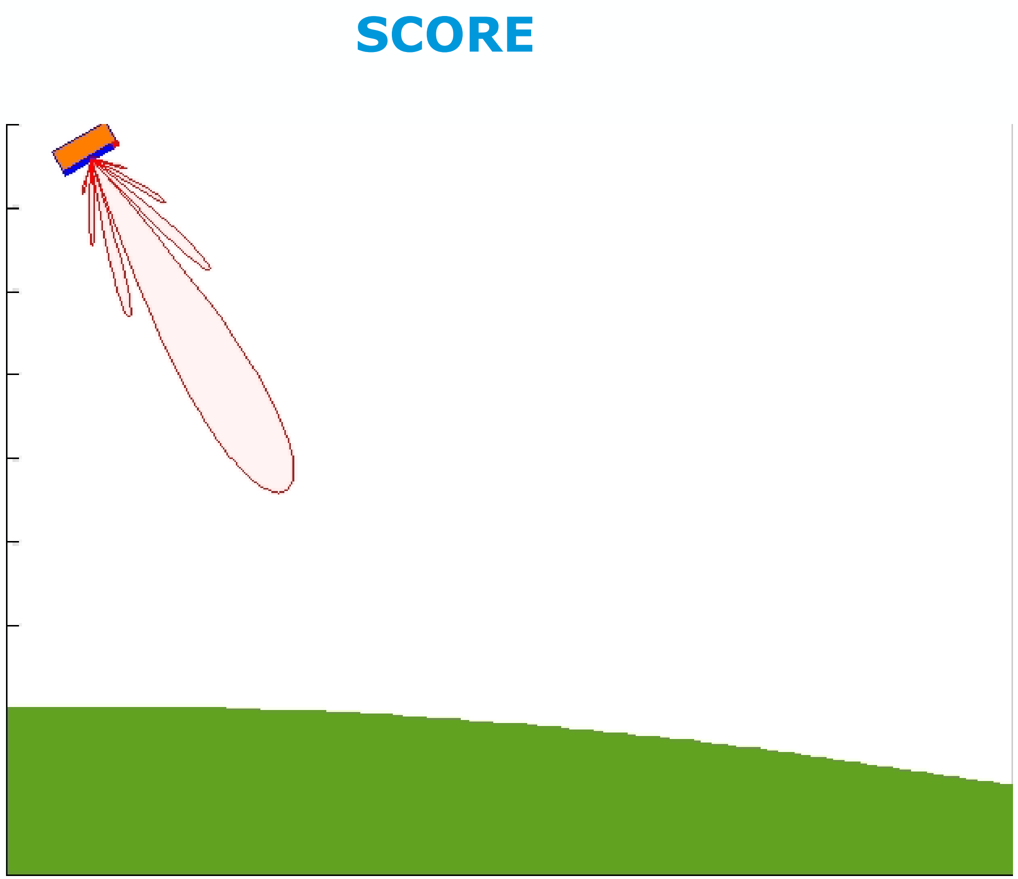


Next Steps? Digital beamforming

Digital beamforming can enable higher performance (spatial resol, swath) and flexibility in future SAR systems



- Tx Antenna Illuminates Wide Swath and Wide Doppler BW
- Multiple Rx Antennas Illuminate Wide Doppler Spectrum
- Multiple Rx Antennas Scan-on-receive to illuminate full swath and re-gain SNR



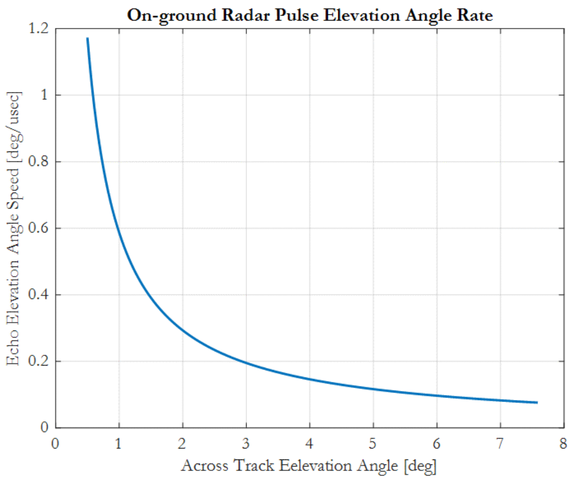
MAPS: Multiple Aperture Processing for SAR
SCORE: Scan-On-REceive

Scan On Receive (SCORE) – a closer look

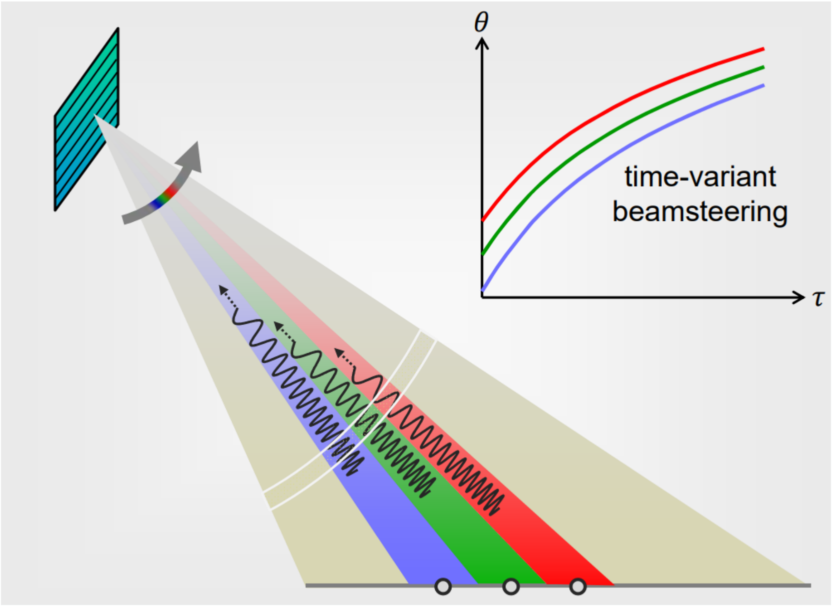
SCan On Receive (SCORE) technique

- Recovery of signal energy on RX
- Limiting the RF power need of the instrument, thanks to higher Rx antenna gain
- Improvement of ambiguity performance
- Very Fast time beamforming , e.g. scanning speed ~0.1deg/usec
- Potential need to have frequency dispersive beam on Rx in order to avoid pulse extension loss
- Natural implementation is based on DRA+ DBF, but focal array-fed reflector configuration with digital (or even analog) feed switching can be done

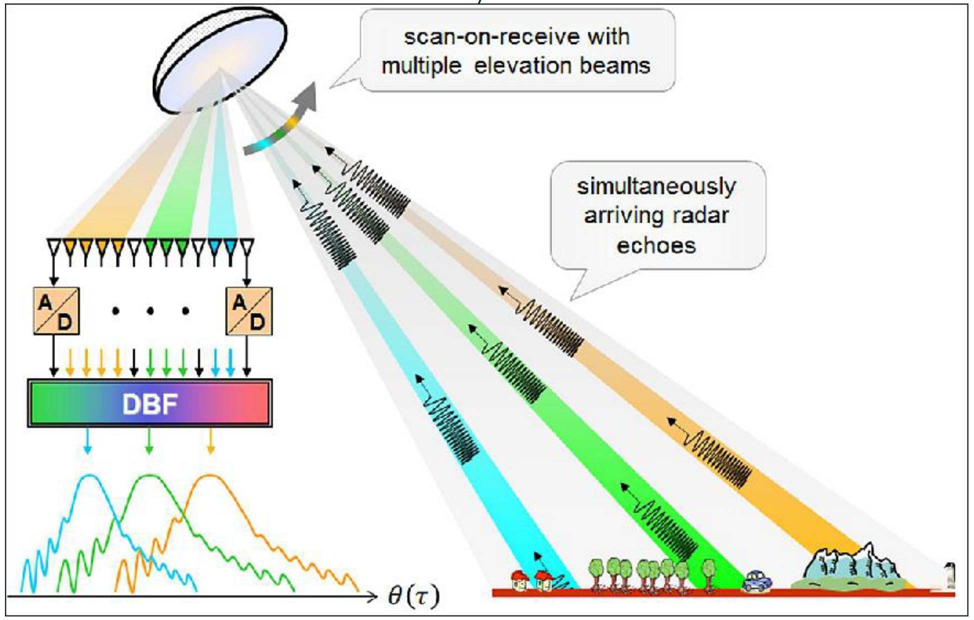
Echo elevation angle rate



SCORE with DRA with frequency dispersion



SCORE with array-fed Reflector



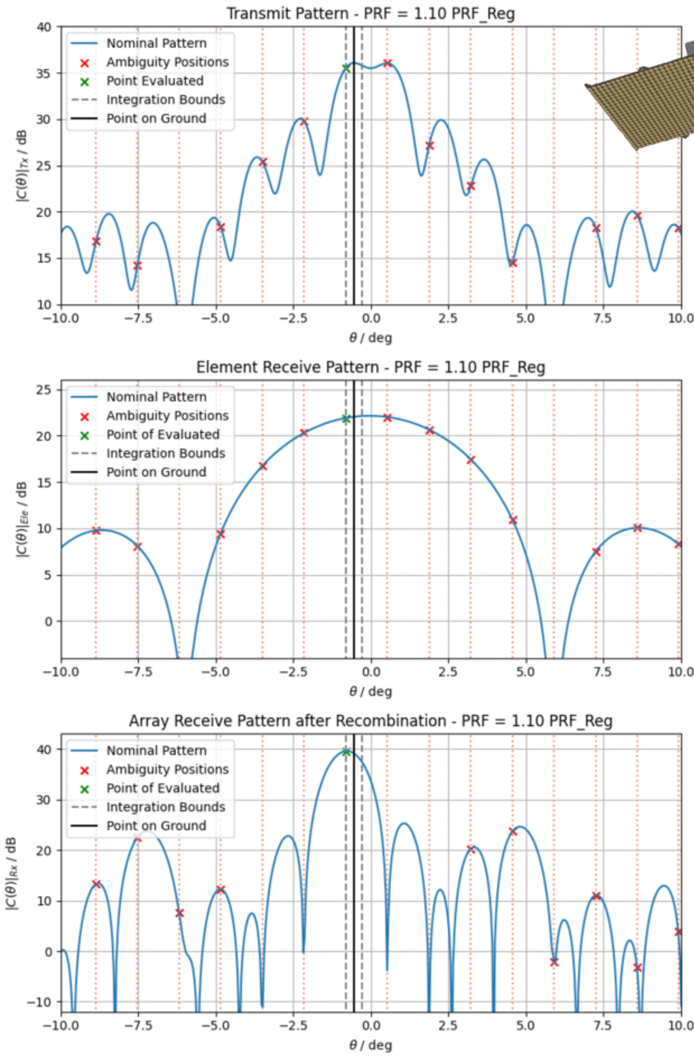
Reflector SAR with multiple elevation beams. Digital beamforming on receive plays a crucial role for the reliable separation of the simultaneously arriving radar echoes from range-ambiguous positions (image credit: DLR)

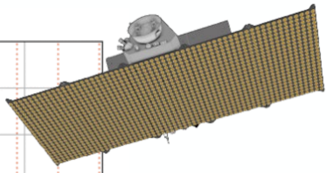
MAPS: Multiple Azimuth Phase Center Sampling

Beamforming technique to suppress ambiguous signal returns, enabling higher azimuth resolution

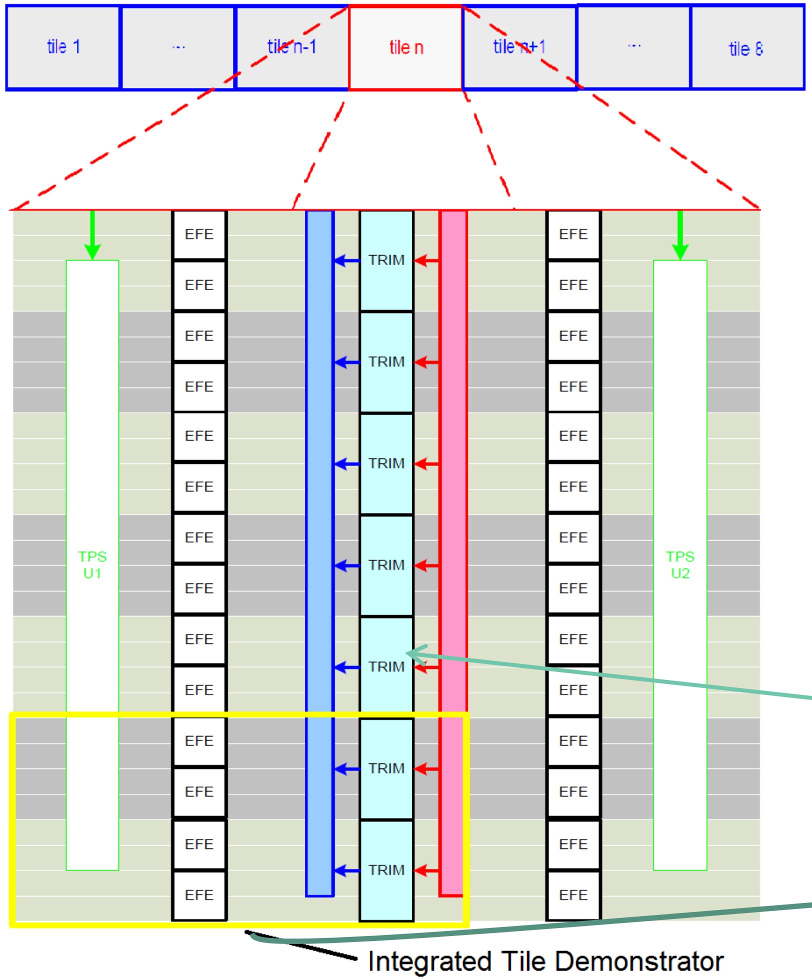
- Example for one point after integration on ground (grey solid line)
    - Edge of the ScanSAR Burst
- Acquisition of integration bandwidth necessary for the resolution (grey dotted line)

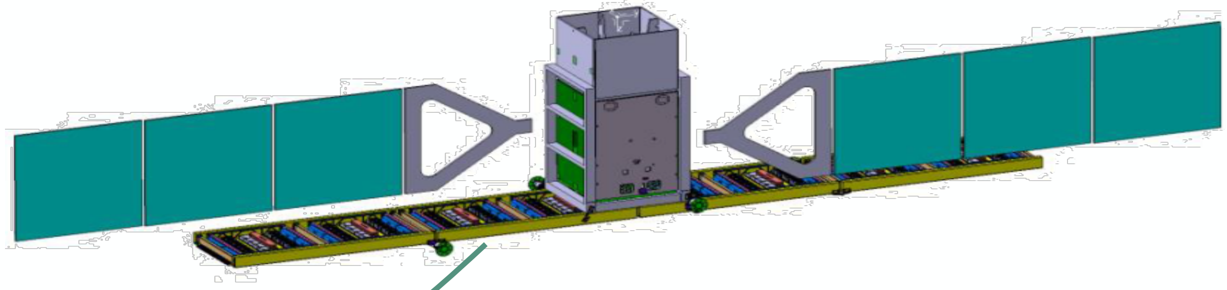
- Top figure: Wide transmit azimuth antenna pattern to illuminate the swath
    - Wide Illumination necessary due to high resolution
- Centre figure: Receive Pattern of a single azimuth channel
    - Ambiguities are received with very high gain
- Bottom figure: Receive Pattern after recombination of 5 azimuth channels
    - The first 4 ambiguities are perfectly suppressed

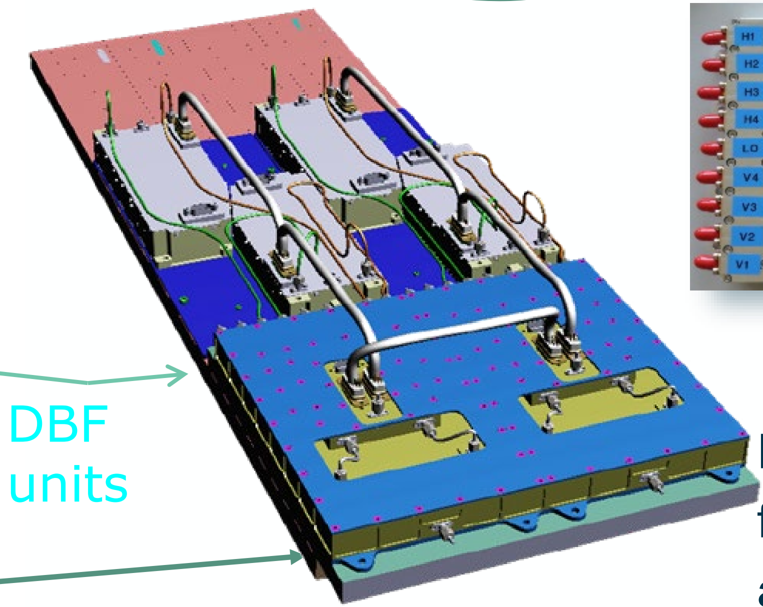


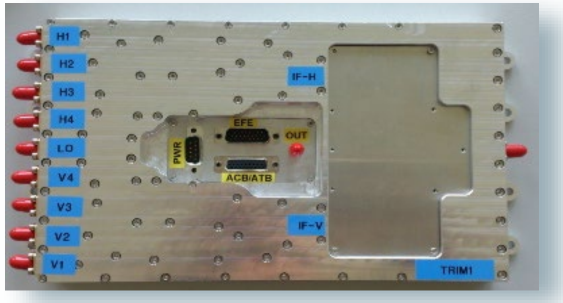


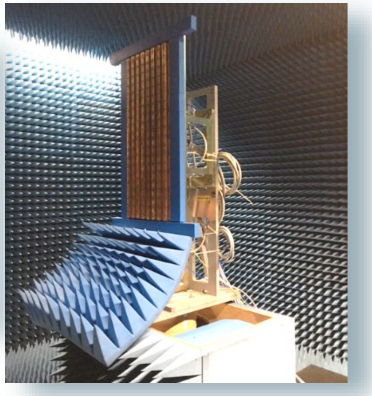
Integration of DBF within the antenna











First demonstrator integrating DBF functions directly within the phased array antenna.

Courtesy of Airbus D&S GmbH, IMST GmbH, Da-Design Oy: Radio Freq. Unit, DLR, Thales Alenia Space Italia

Planar Antenna or Reflector for SARs?

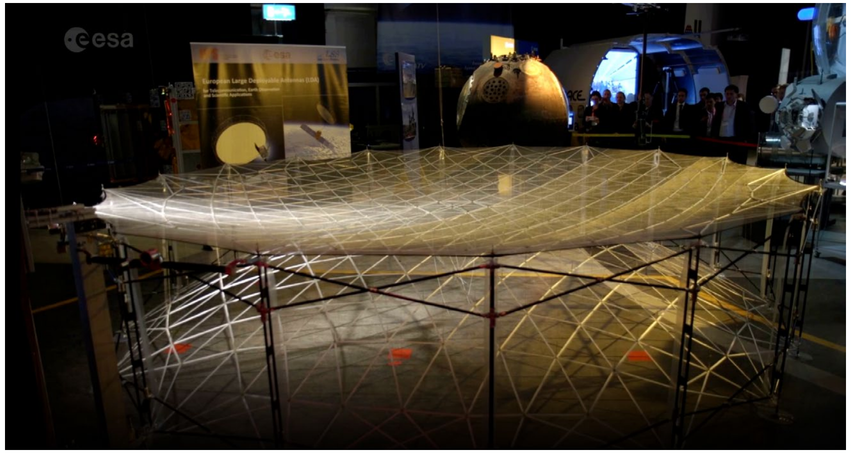
Planar Antenna

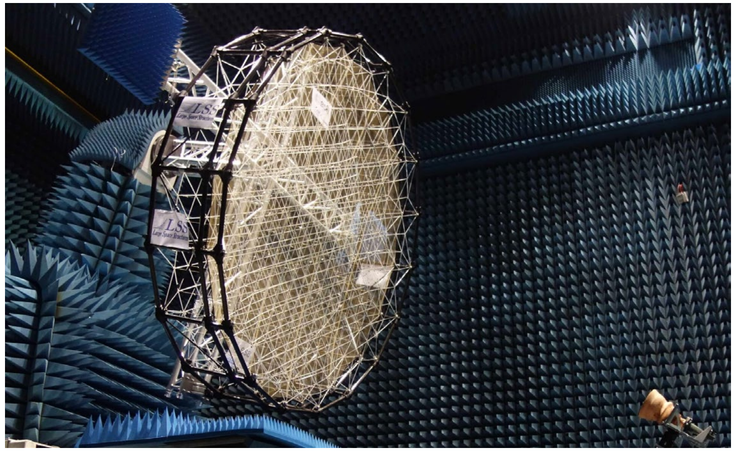
- Pros:
  - Flexible Beam Steering
  - Map an arbitrarily wide swath (weight change only)
  - Inherent ATI
  - Less challenging pointing knowledge and accuracy
- Cons:
  - Mass
  - Instrument complexity (e.g. multichannel in azimuth)
  - Power demand
- Better suited for lower orbits (i.e., S1 orbit)

Reflector Antenna

- Pros:
  - Large Aperture:
    - High Gain -> good for SNR!
    - Low power demand
  - Low mass
  - Potentially Simplified instrument architecture
- Cons:
  - ATI
  - Pointing Knowledge and accuracy
  - Electronic beam steering and access range (access range ➔ feed elements)
- Better suited for higher orbits (i.e., 800-1500 km orbit)

Recent Large deployable Reflector European developments pave the way for new high resolution Earth Observation instruments





Courtesy of HPS and LSS

Future SAR Missions

Future SAR earth observation missions and their demanding imaging requirements will require :

- ❑ large antennas
  - ➢ Reflectors antennas, array fed reflector antennas

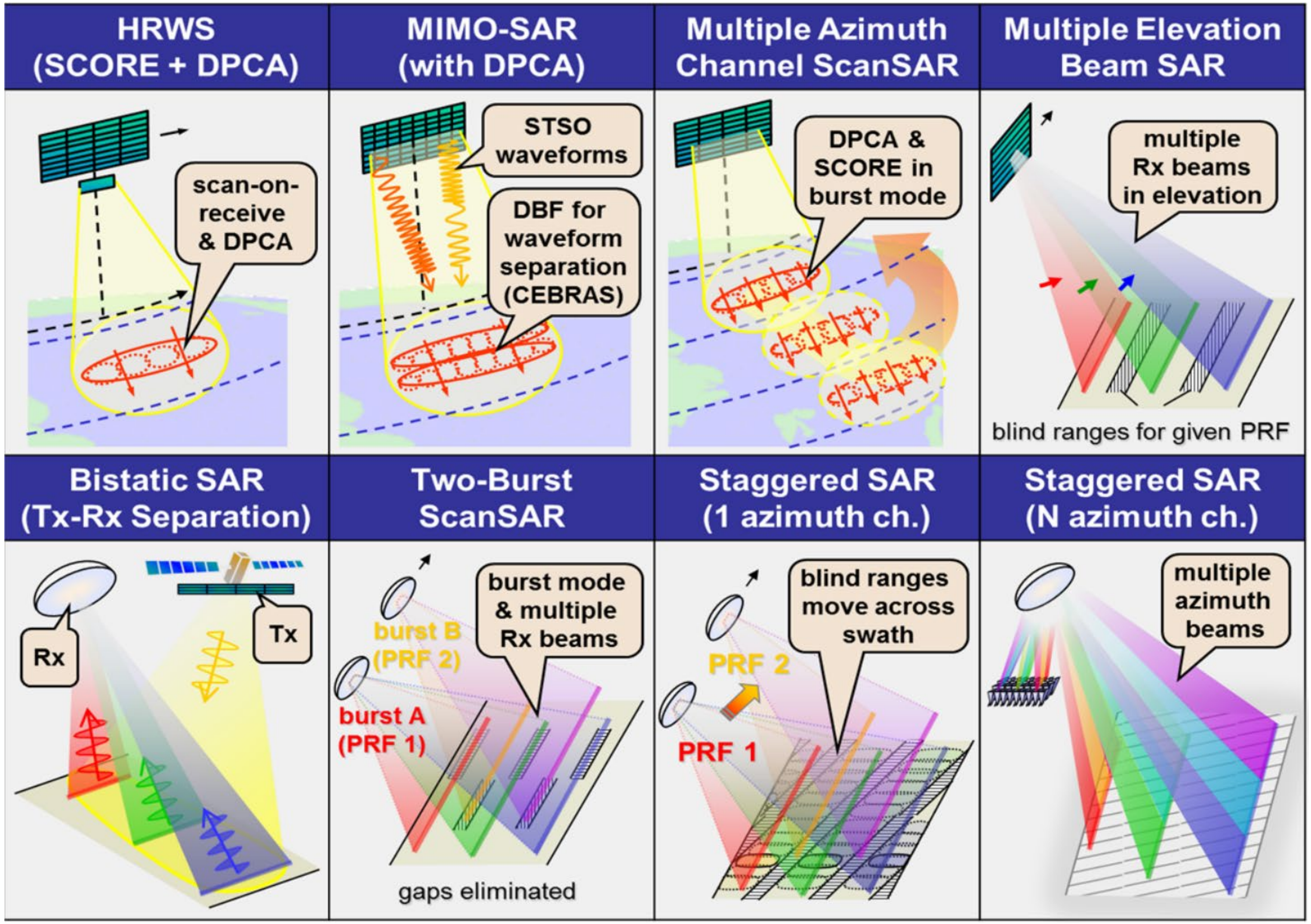
and/or

- ❑ Enhancement of DRAs (Direct Radiating Arrays) in terms of bandwidth, efficiency, flexibility and cost
- ❑ Digital Beam Forming (DBF) capability
  - ➢ MAPS: Multiple Aperture Processing for SAR
  - ➢ SCORE: Scan-On-Receive
  - ➢ MEB SAR: Multiple elevation beam SAR
  - ➢ HRWS :High Resolution Wide Swath

- ❑ Slow-varying PRI /Staggered PRI

The combination of the abovementioned features allows to achieved the desired performance

Future SAR Missions concepts

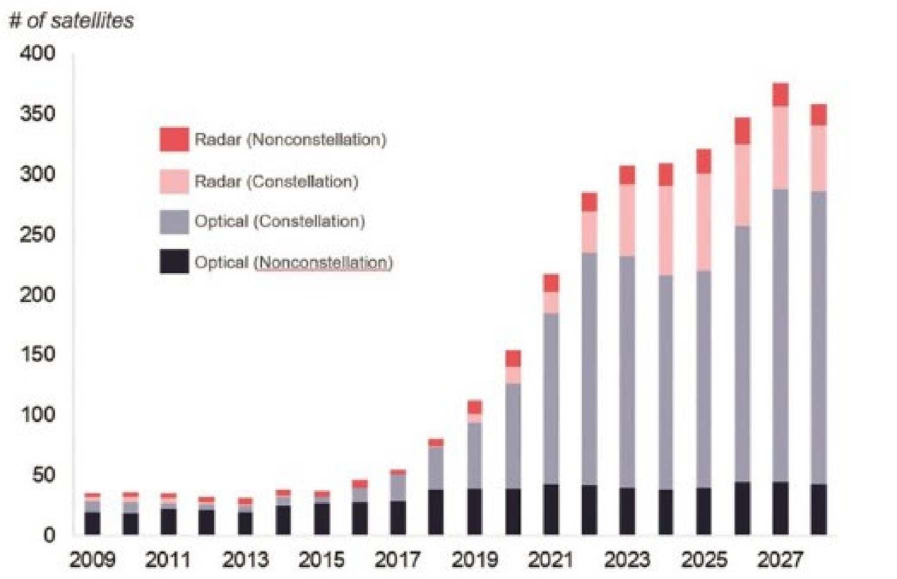


DLR courtesy, Advanced Processing Techniques for Next Generation Multichannel SARs, ESA Contract No. 4000116591/16/NL/FE

New Space trend

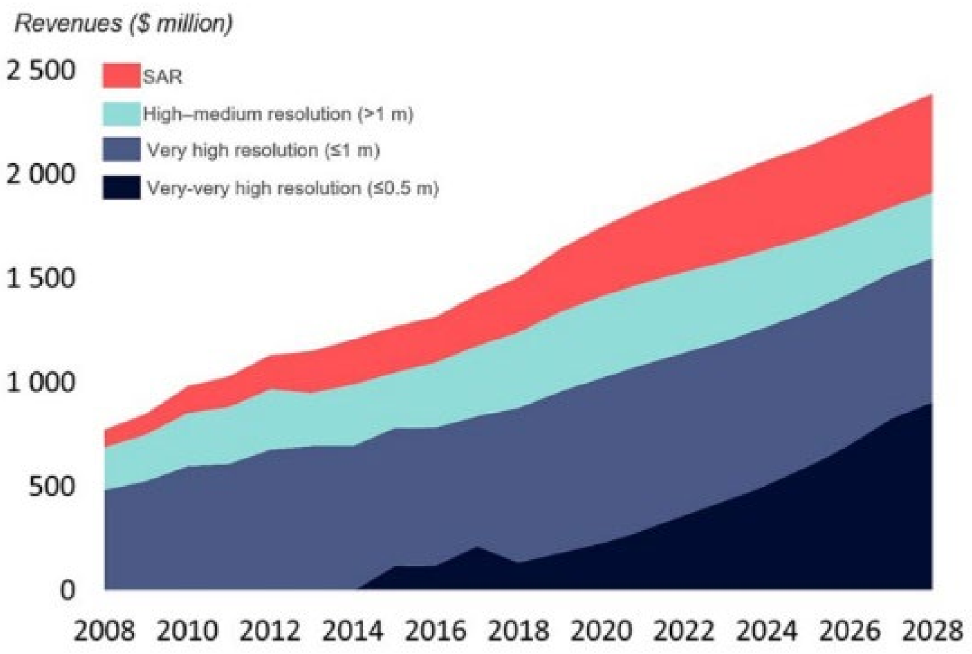
- Increasing demand of Earth Observation data and in the specific case of Synthetic Aperture Radar data
- Variety of application fields
- Commercial entities developing small platforms (nano- and smallsats) carrying SAR payload on board

COMMERCIAL EO SATELLITES IN OPERATION (>50 KG)



*Includes satellites launched by both private enterprises and governments whose data are made available on a commercial basis. Satellites in operation are based on reported/expected life spans.

EARTH OBSERVATION DATA SALES BY TYPE



SAR Newspace Commercial Rise

- Many companies from all over the world :
  - USA : PredaSAR , Capella Space, Umbra Lab, XpressSAR, Trident Space, EOS SAR
  - Europe : IcEye
  - China : Spacety
  - Japan : Synspective, iQPS

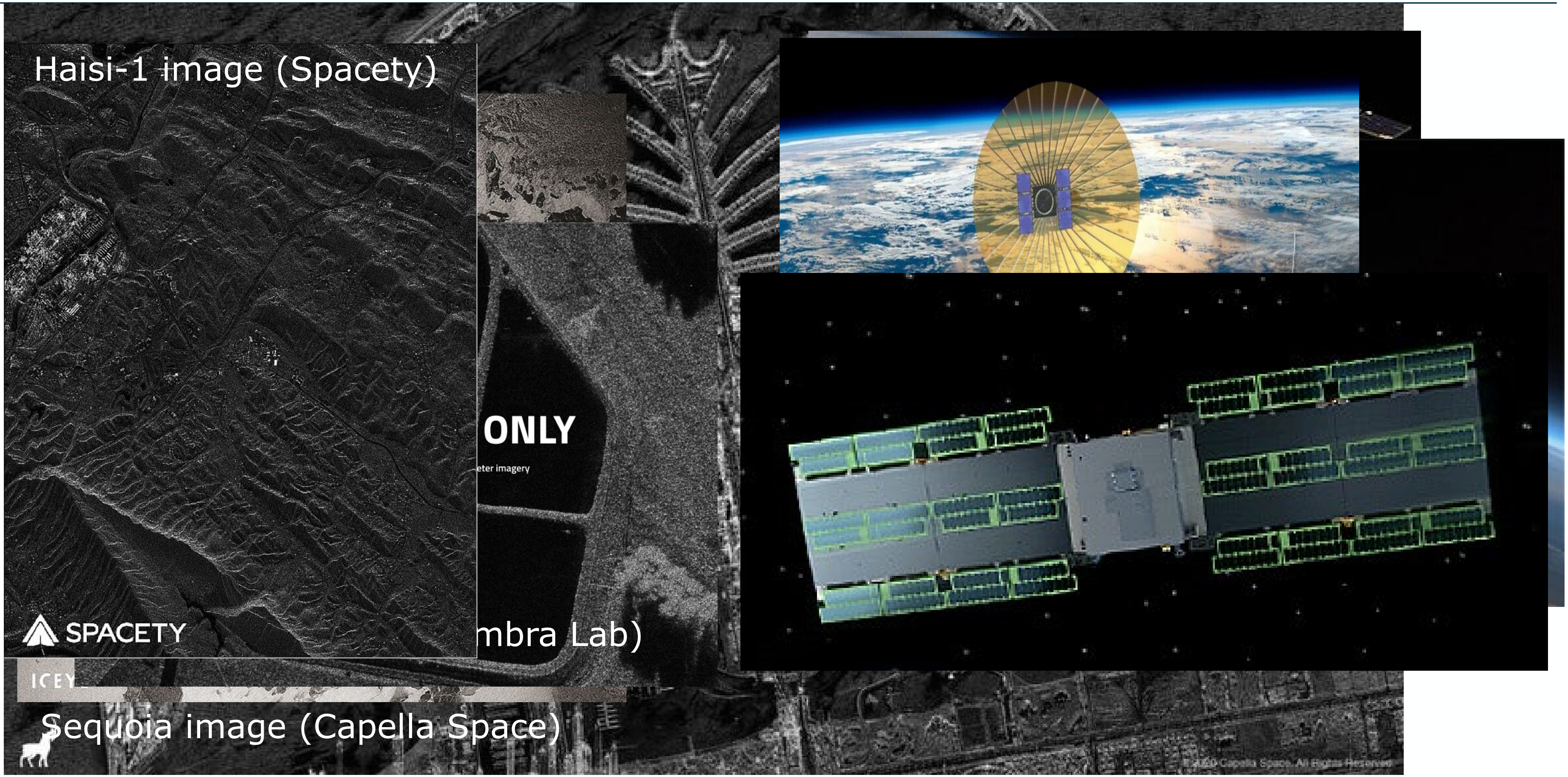
- Extreme verticalization between the different “phases” of a SAR development :
  - Designing → Developing → Integrating → Testing → Launching

- Reduced cost per platform → possibility of launching constellations → enables multistatic applications and improves revisit times

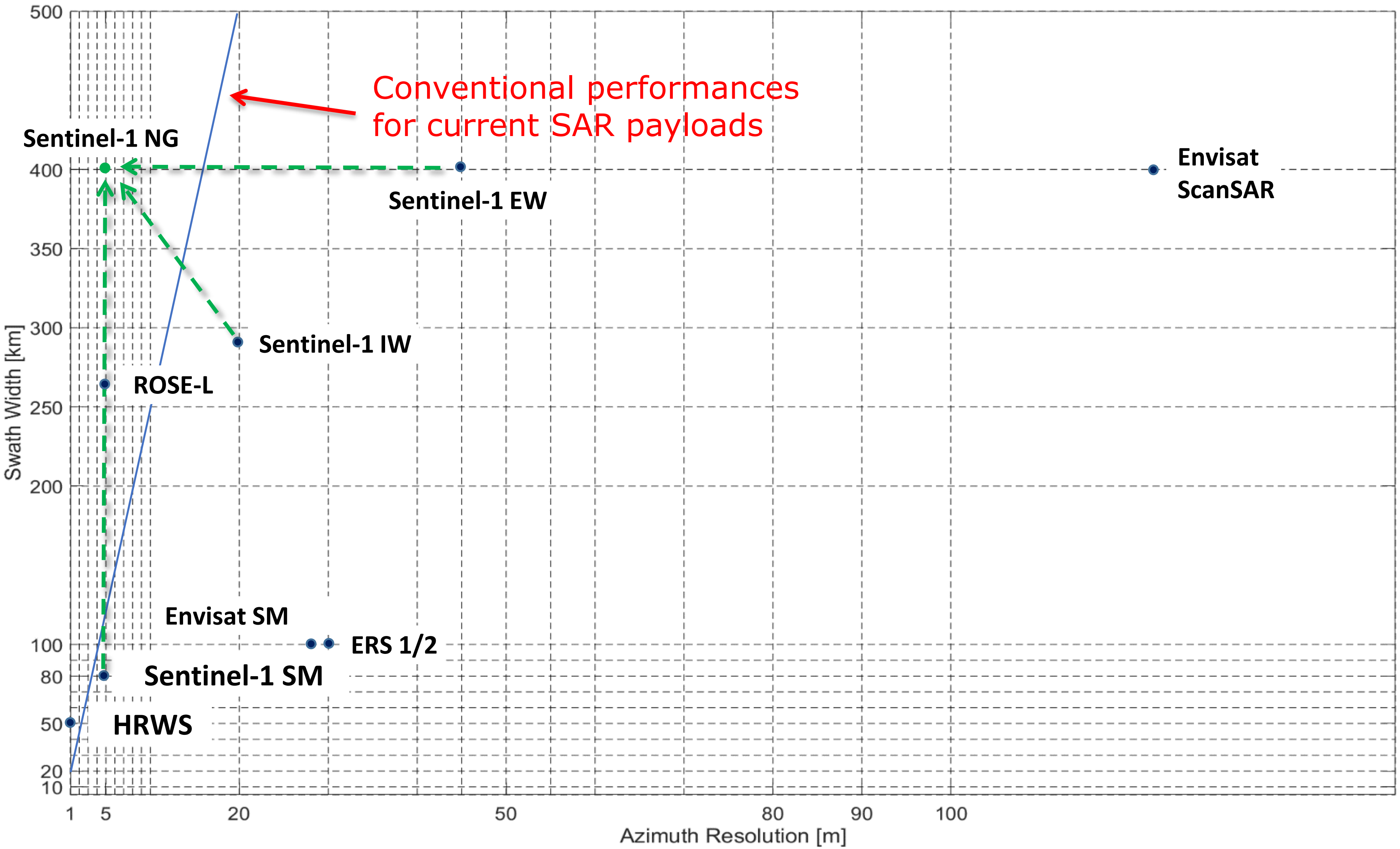
New Space SAR summary

Company Name	Power	Cost	Frequency Band	Launch	Mass	N of satellites in constellation	Altitude	Revisit Time	Cost per Kg
EOS SAR		15 M	X-Band	2021	150 Kg	6	Ca. 500 Km	2/3 hr	0.1
Synspective	1000 W	15 M	X-Band	2020	150 Kg	25	600 Km	2/3 h	0.1
Spacety		n/a	C-Band	2021	185	n/a	Ca. 500 Km	Ca. 12 hr	n/a
XpressSAR		75 M	X-Band	2022	100-200 Kg	8	425 Km	<4 ore	0.38
Trident Space		42 - 65 M	X-Band	2021	300 Kg	48	Ca. 500 Km	<1 hour	0.22
UmbraLab	550W	3.5 - 5 M	X-Band	2020	50 Kg	12	515 Km	<1 hr	0.1
Capella 1	1000W	<15M	X-Band	2018	<40Kg	36/44	525Km	3/6 hr	0.38
Iceye X1	2000W/4000W	10/15 M	X- Band	2018	70Kg	18	3 hr	3 hr	0.21

New Space SAR : examples



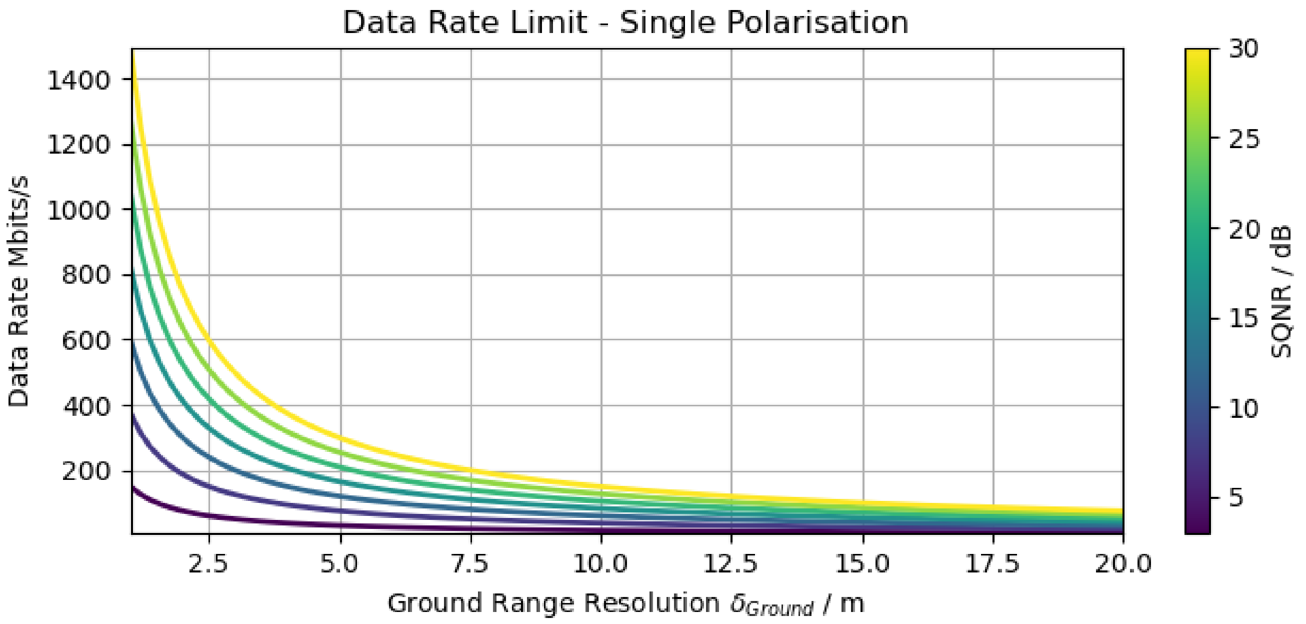
Next generation SAR Missions



Data Rate: Upper Limit

Data Rate Upper Limit for conventual SAR instruments

- General Simplified Equation for single channel Instrument: $DR \approx N_{Samples} 2 N_{Bits} PRF$
    - Just Data, no overhead
- By applying some general simplifications and basic restrictions for the mode design of conventional SAR, an upper limit for the instrument data rate can be derived:
    - Upper Data Limit: $DR < \frac{c_0}{\delta_{Ground}} \cdot \frac{SQNR_{dB}}{6.02\ dB}$
- The data rate limit is invers proportional to the ground resolution δ_{Ground} and proportional to the $SQNR_{dB}$



Data Rate: DBF

- Digital Beamforming techniques allow for new ways of SAR swath design, pushing the boundaries of conventual SAR instruments
  - SCORE: Wider Swath with same resolution
  - MAPS: Higher Azimuth Resolution without Ambiguity Issues
  - FSCAN: Trading Frequency (Resolution) vs Time (Swath Width)

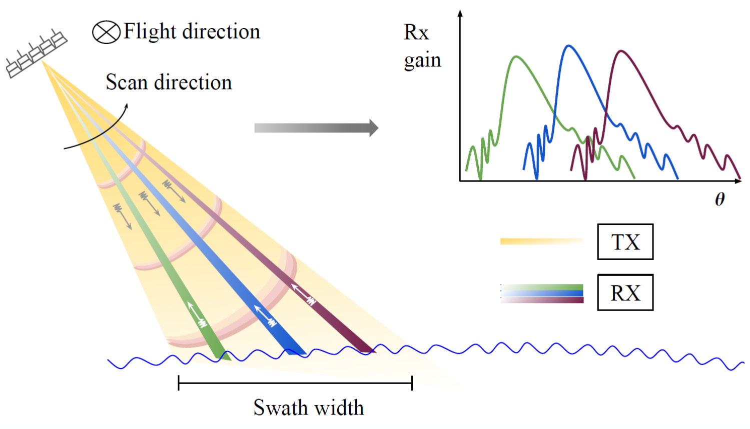


Fig: Exemplary Display of the SCORE technique

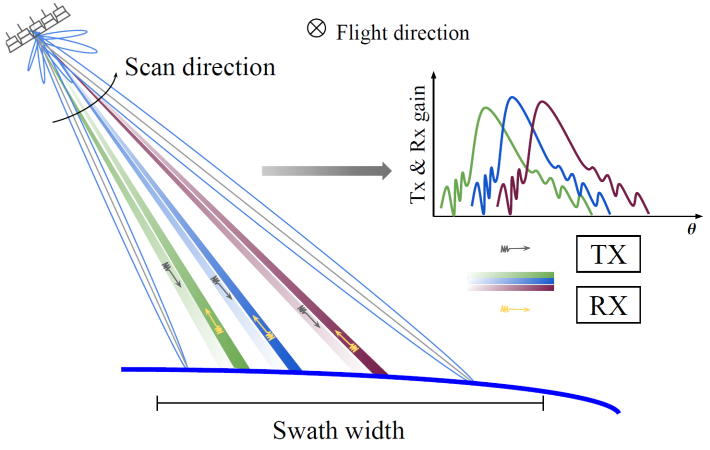


Fig: Exemplary Display of the FSCAN technique

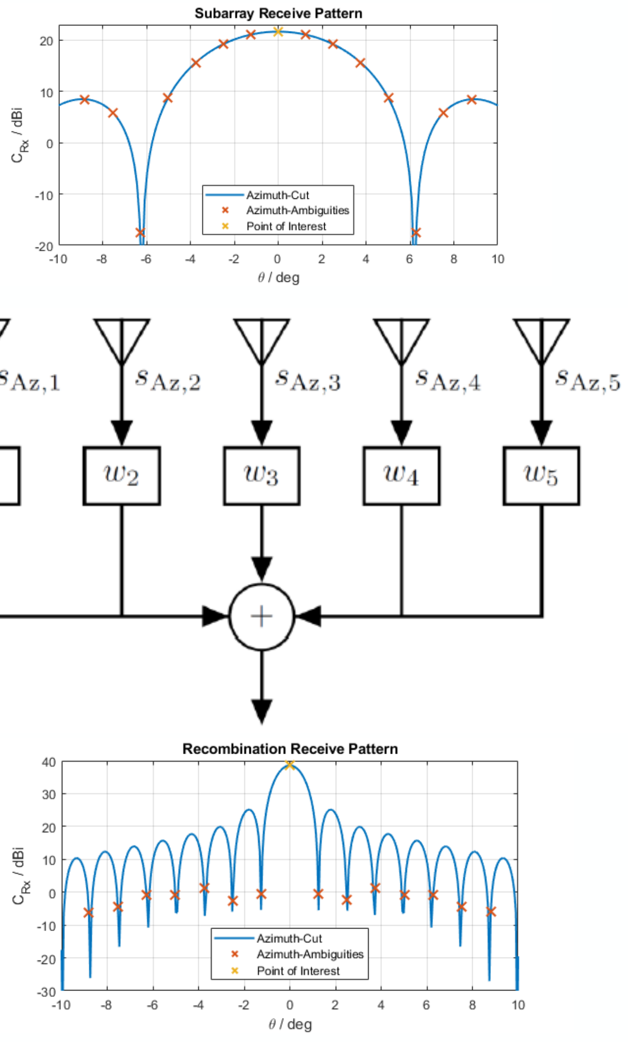
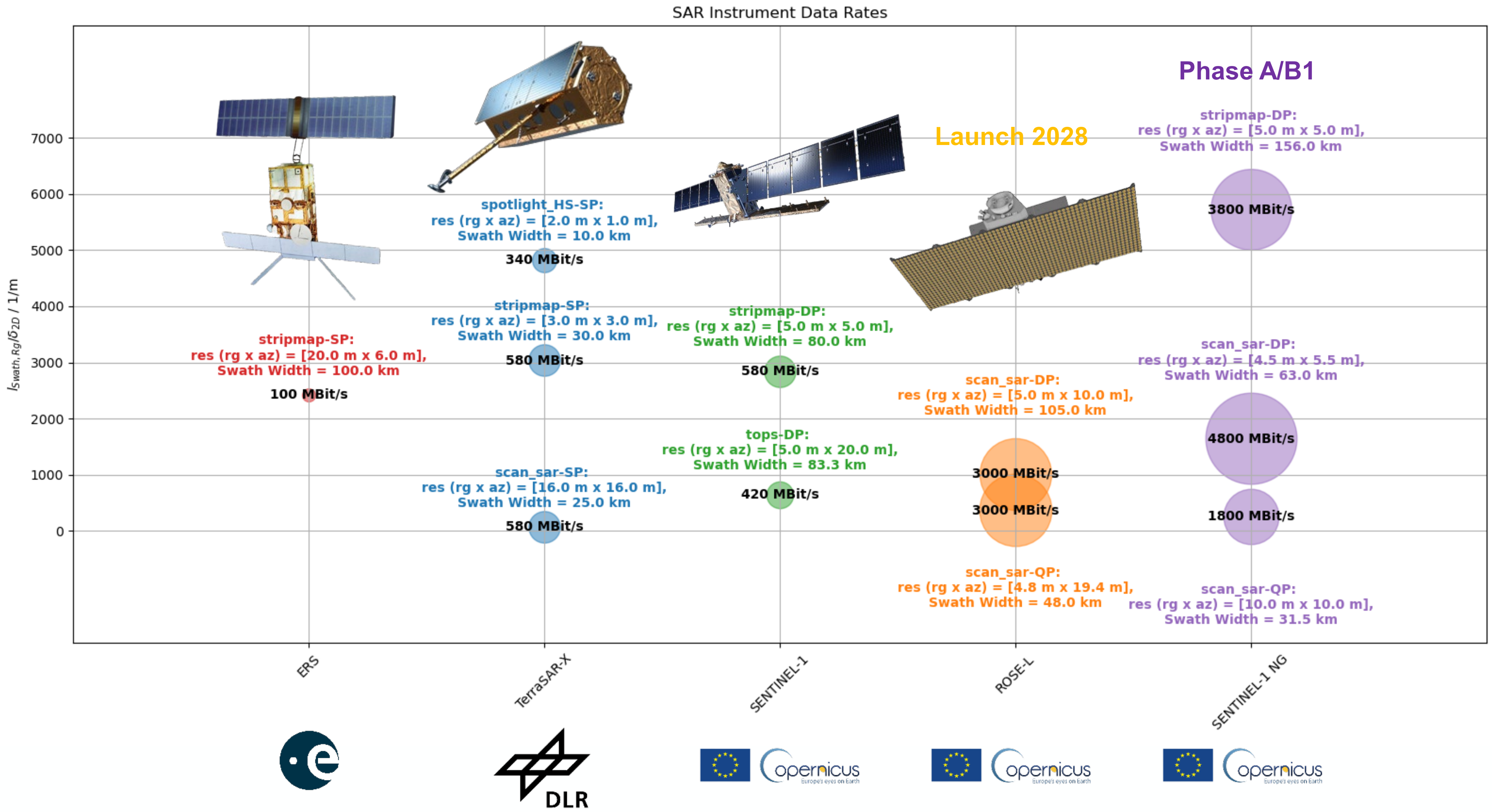


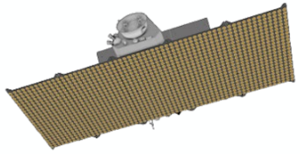
Fig: MAPS DBF Example

Data Rate: Instrument Comparison

- Mode Quality Parameter: $l_{swath,Rg} / res_{Gr,2D}$
- Circle Diameter proportional to data rate
- Increasing with wider swath and higher resolution
- Instruments based on DBF architecture show significant increase in data rate



Data Volume: Instrument Comparison



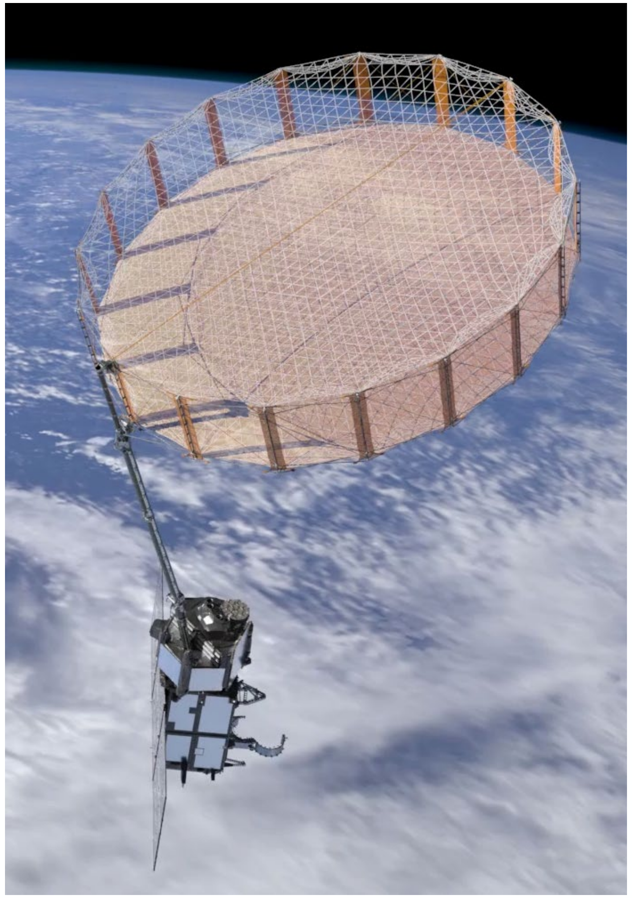
Satellite	Acquisition	Number of Digital Channels per Polarization	Orbit Duty Cycle	Mode Operation Times	Data Volume
Sentinel 1	Pre-planned	1	60% – 60 min	5 min SM, 15 min IW, 40 min WV	>400 Gbit
ROSE-L	Pre-planned	4 Elevation x 5 Azimuth (Azimuth Channels are downlinked)	50% – 50 min	20 min DP/QP, 30 min WV	4 Tbit
Sentinel 1 - NG	Pre-planned	Projected: >5 Elevation x >5 Azimuth (Azimuth Channels are downlinked	43% Average – 40 min	5 min SM, 5 min IW, 30 min WV	3 Tbit
			53% Peak – 50 min	15 min IW, 35 min WV	4.8 Tbit

- Table gives the total Data Volume for one exemplary orbit and acquisition plan for the different instruments
- New SAR instrument architectures lead to a massive increase in data rate and total amount of data
    - WV = Wave Mode – Imaging mode with very small swaths and reduced transmit Duty Cycle
- High demand for increasing orbit duty cycle as well as swath width for future missions will lead to more data
- **Need for advanced data compression schemes and/or on-board processing!**

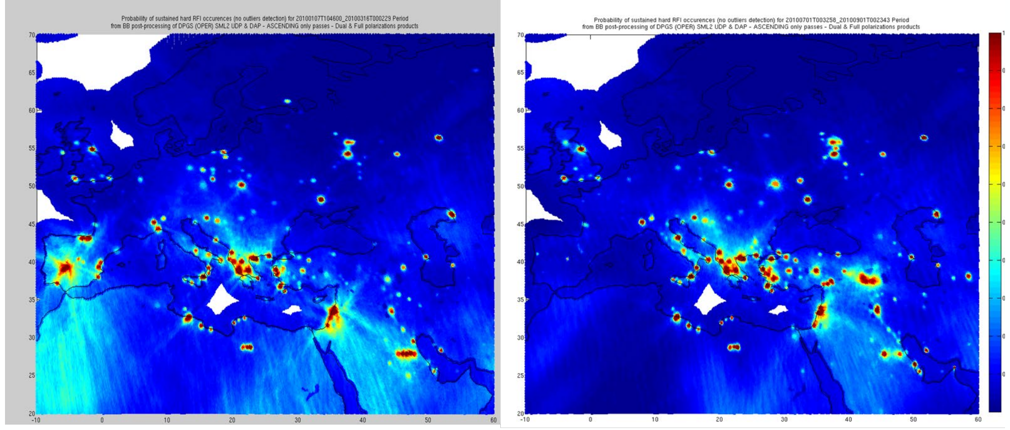
CIMR Mission: The need of detecting RF Interference

Monitoring the Cryosphere, as part of the European Integrated EU Policy for the Arctic

Providing sea ice concentration, sea surface temperature, thin sea ice thickness, sea surface salinity and wind speed over the ocean



- *Embarking 55 microwave radiometer channels observing from L- to Ka-band, for a total of 11GHz aggregated bandwidth*
- *Observations can be significantly affected by ground emitted Radio Frequency Interference, leading to reduction/loss of data*
- *CIMR embarks an on-board RFI processor to detect and mitigate interference in quasi real time, reducing the amount of data to be stored and transferred to ground*

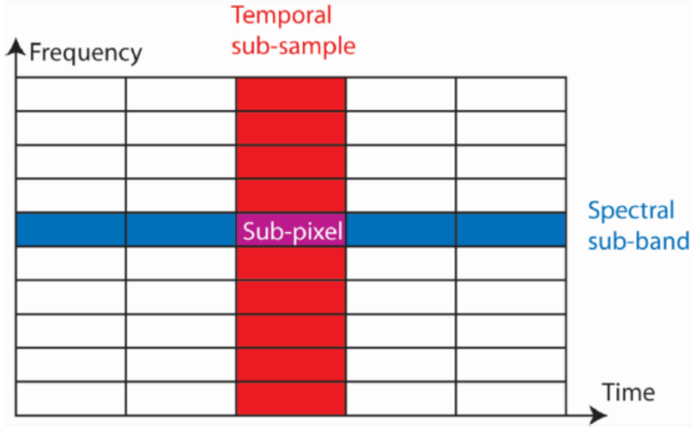


Credit – CESBIO (F)

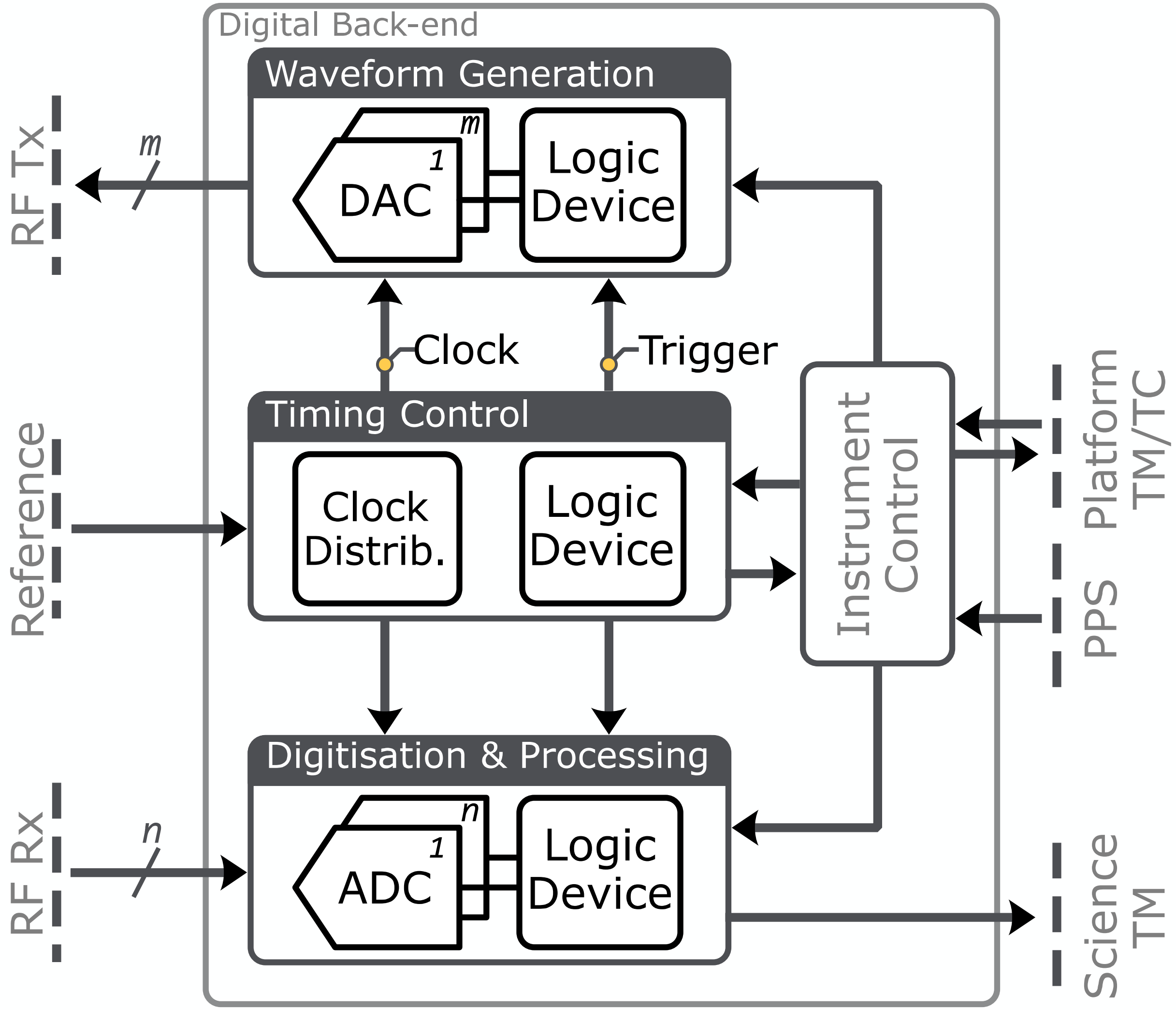
14+1 sources off over 24 in Spain,
1 over 1 in Finland,
1 over 2 in Germany,

1 over 3 in Poland,
1+2 over 15 in Italy,
+2 over 3 in Denmark, and counting…

L-band interferes in Europe



Your typical Radar (Digital) Back-end…



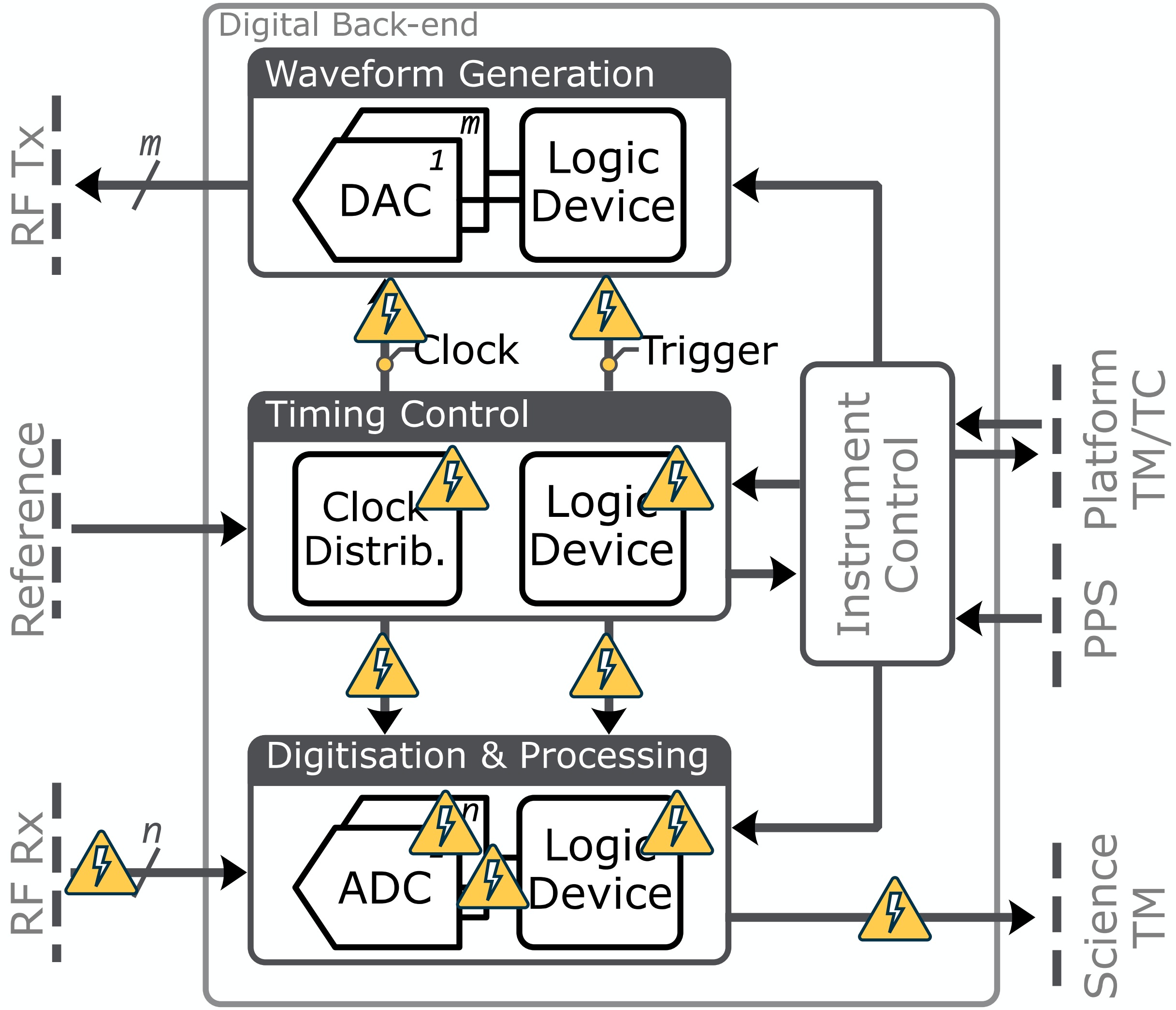
Functions

- Waveform Generation
  - DDS, I/Q Modulation, *Up-conversion*
  - Analogue Waveform Conversion
- Timing Control
  - Coherent triggering of Tx and Rx
- Digitisation & Processing
  - Analogue Echo Digitisation, *Down-conversion*
  - Processing, Formatting and Science TM Tx

Building Blocks

- *Logic Device* – DSP & Control
- *Clock Distribution & Synchronisation*
- *ADC* – Analogue-to-Digital Converter
- *DAC* – Digital-to-Analogue Converter

… but not so typical needs!

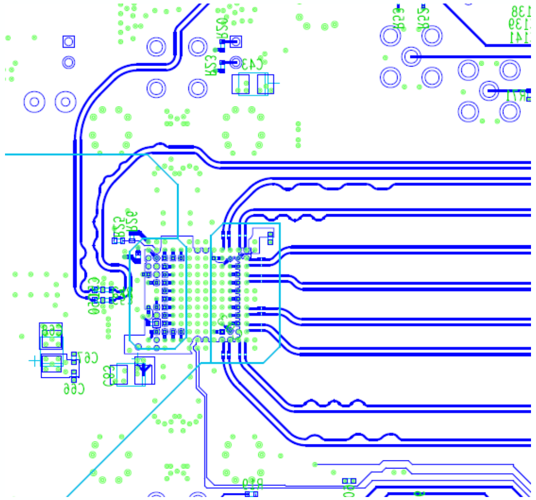


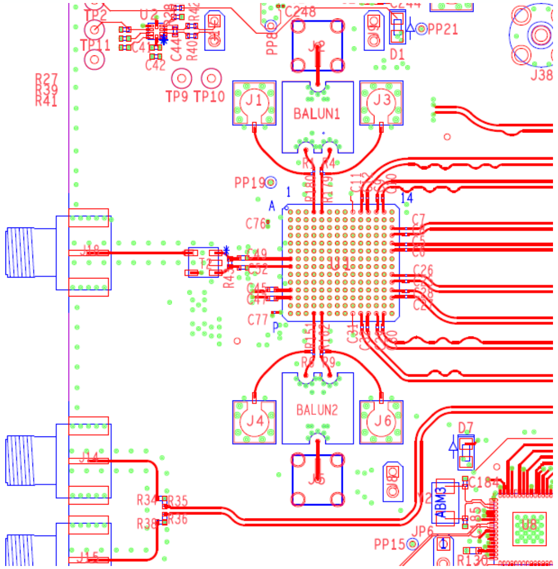
Flow-down of requirements is demanding more from the back-end …

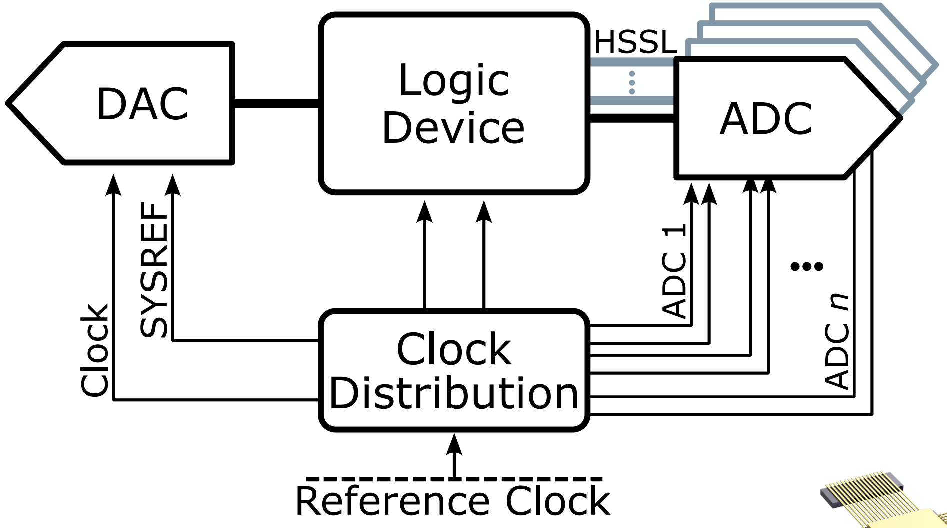
- Direct Conversion up to C-band, which means higher input bandwidth
- Multiple RF Rx Channels (per polarization)
- Data Processing and Reduction such as On-board DBF
- Higher Science TM Data Rates, in the order of Gbps

Multiple RF Channel Rx at the back-end

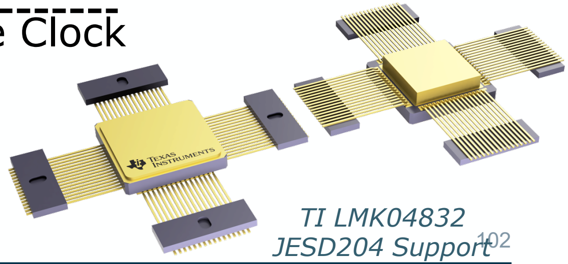
- Acquisition of multiple RF channels requires coherence and determinism in signal sampling among all channels, which means a certain Channel-to-Channel accuracy in sampling to avoid phase errors, typically better than picosecond level (10^{-12})
- Challenges address by:
  - Advanced clock distribution and synchronisation, like JESD204, both for internal and external modules
  - PCB Layout for signal integrity and length matching







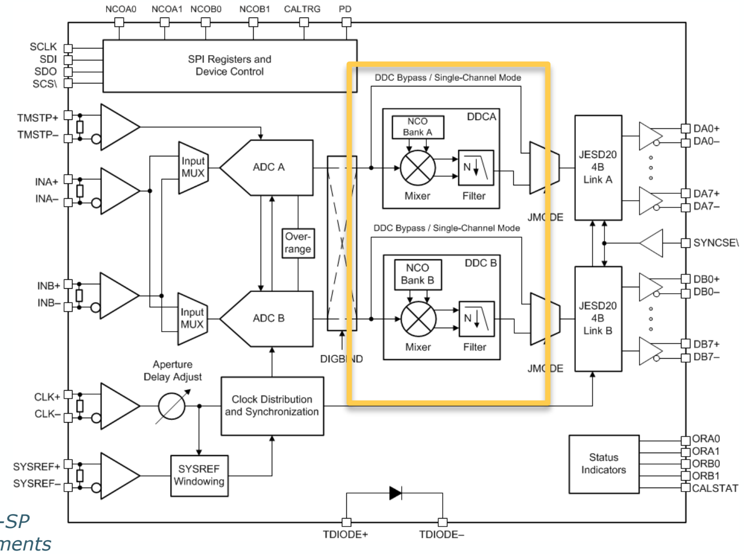
JESD204 System



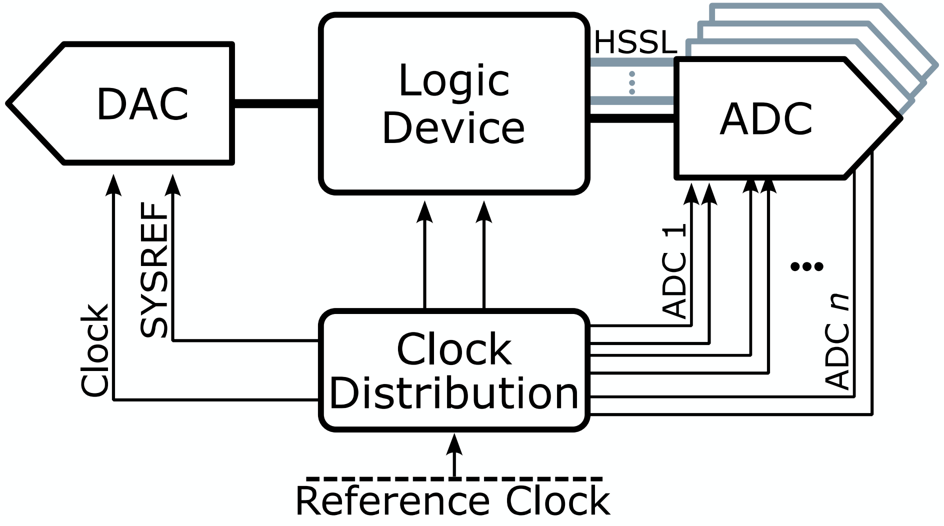
TI LMK04832 JESD204 Support

High Sample Rate Data Acquisition

- A consequence of higher sampling rates usually employed in direct conversion is higher data rates (Gbps), which in turn complicate the interface with the Logic Device (usually FPGA) as well as the design.
- Challenges addressed by:
  - Advanced ADC/DAC which perform Digital Down/Up Conversion, thus reducing the amount of data.
    - Example: DDC at ADC with sub-Nyquist sampling of L-band for EO can reduce I/Q data rate from 30 Gbps to 3 Gbps
  - Usage of HSSLs for ADC/DAC and Logic Device interconnection, together with JESD204 protocol

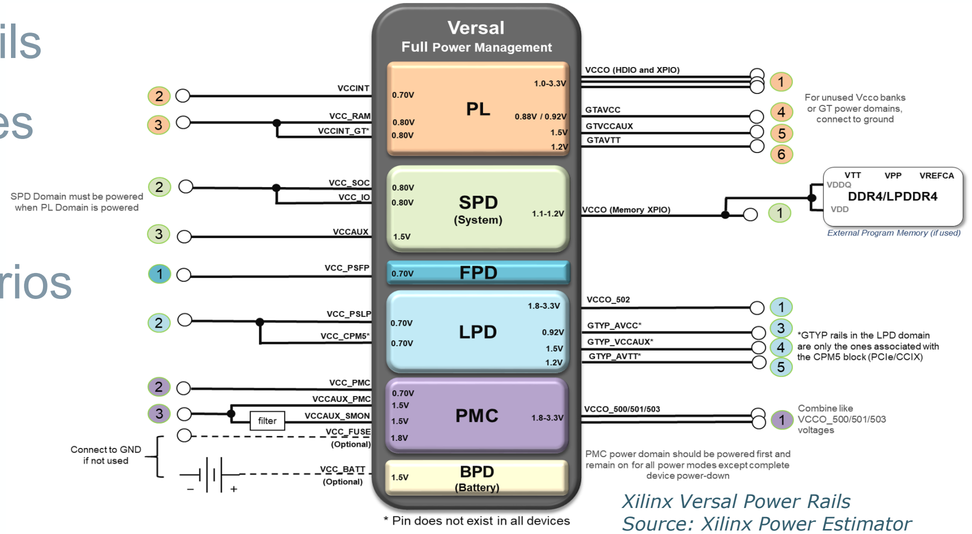


TI ADC12DJ3200QML-SP
Source: Texas Instruments



High-Speed Data Acquisition and Processing

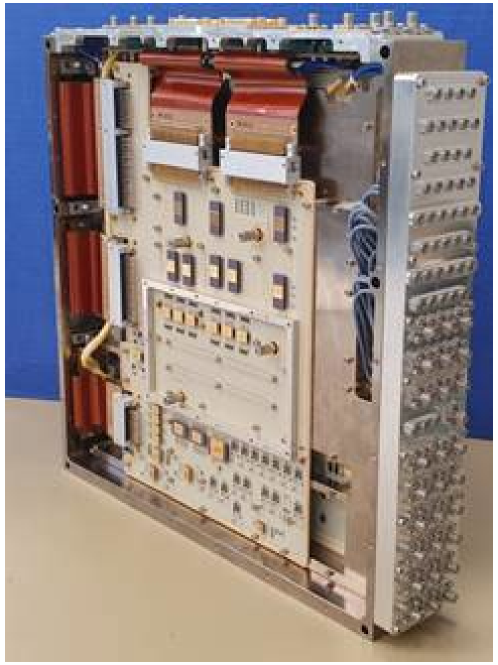
- The high-speed data acquisition and processing required by the digital back-end such as DBF are also ushering the introduction of new Logic Devices, namely FPGAs like Xilinx Kintex Ultrascale or the Microchip PolarFire, with their DSP capabilities as well as HSSLs.
- Challenges posed:
  - Radiation Effects’ sensitivity, requiring introducing SEE mitigation techniques at device level, but also considerations at System level since these devices are big contributors to the <u>availability</u> of the instrument
  - Power Distribution Design, both in number of different PoLs as well as load-step
    - Example: Xilinx Versal can have ~20 different power rails
  - PCB technology and assembly, due to sophisticated packages
  - Thermal Design, to cope with latest FPGA power dissipation
    - Example: Xilinx KU060 can reach 20W for some scenarios



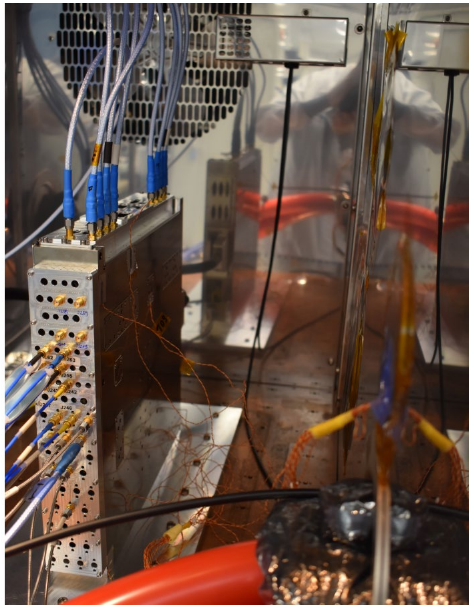
Xilinx Versal Power Rails
Source: Xilinx Power Estimator

Building Block: Universal Processing Module (UPM)

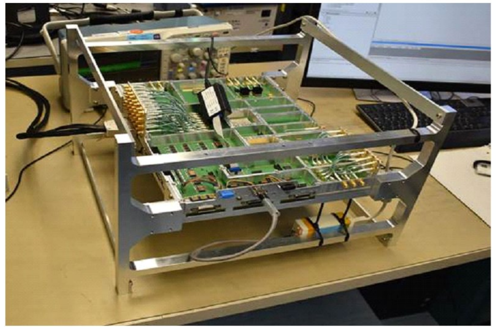
- State-of-the-art Digital Back-end Building Block
  - DSP with Space-grade Xilinx Ultrascale KU060 FPGA
  - Support for multi-channel digitisation, both within UPM and among several UPMs
  - Direct conversion up to C-band
    - 8x Rx Channels, 1x Tx Channels
    - Up to 3.2 Gsps digitisation
- Enabler for compact radar instruments
  - Single module can support all functions: Waveform Generation, Digitisation, Processing and Timing Control
  - Possibility to embed Instrument Control and run Application Software
- Developed by Airbus Defence and Space



UPM EM+



UPM EM+ Test

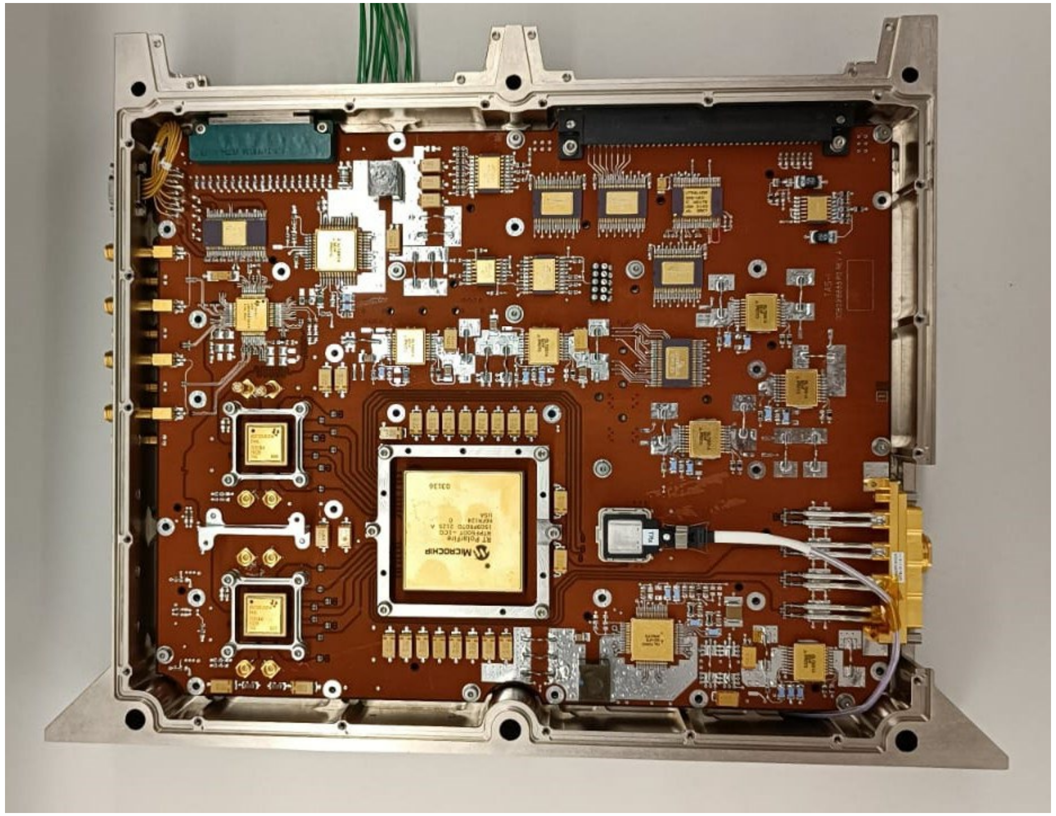


UPM EBB

Pictures courtesy of Airbus Defence and Space

R&D Radar Central Electronics

- State-of-the-art Digital Back-end R&D, providing a modular architecture with 3 building blocks
  - First Stage Processor, for Echo Acquisition and Processing
  - Second Stage Processor, for Data Aggregation and Processing
  - Waveform Generator, for signal generation and control
- Main characteristics
  - DSP with Space-grade Microchip PolarFire FPGA
  - Support for multi-channel digitisation, both within FSP and among several FSPs
  - Direct conversion up to C-band
    - 4x Rx Channels per FSP
    - 1x Tx Channel per WFG
    - Up to 3.2 Gsps digitisation
- Developed by Thales Alenia Space in Italy



RCE FSP EM

Future Outlooks for Digital Back-end

Towards more Bandwidth and Integration

- Higher bandwidth capabilities – even up to Ka band – enabling more SDR capabilities
- More DSP at ADC/DAC component level, to offload the logic devices
- Faster data exchange interfaces, to cope with higher sample rates
- More integration, to ease board design and optimise SWaP

Towards more Data Processing On-board

- Increased DSP capabilities, Beamforming, RFI, etc.
- Science Product Generation on Board
- Machine Learning (ML) On-board Applications

Cognitive remote sensing

Tip and Cue
Distributed Multi-Satellite

Cognitive Radar
Single Satellite

MARCH 1982 NOTES

Adaptively Pointing Spaceborne Radar for Precipitation Measurements

DAVID ATLAS

Goddard Laboratory for Atmospheric Sciences, NASA/Goddard Space Flight Center, Greenbelt, MD 20771

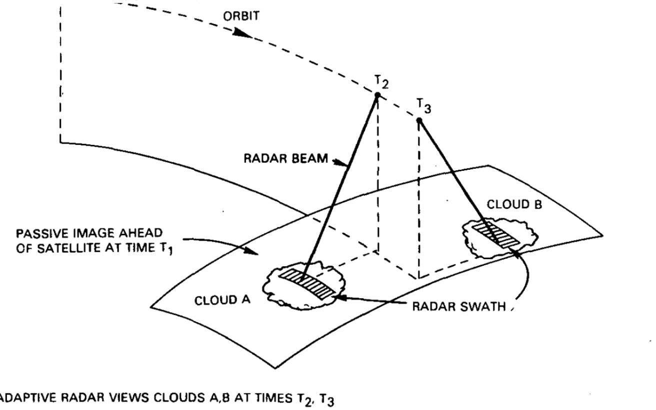
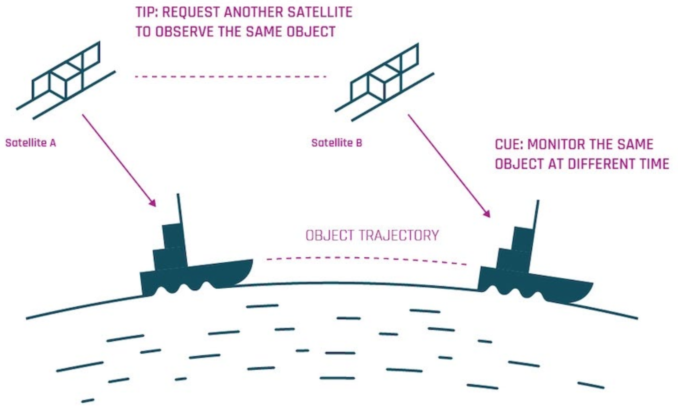
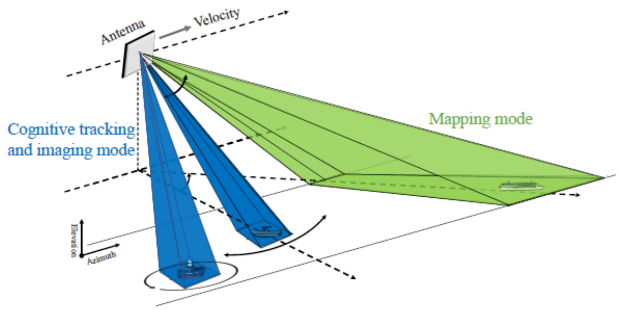


FIG. 1. Schematic of adaptively pointing spaceborne precipitation radar; see text for details.





Optimised use of resources/
Better Performance

Fast reaction time

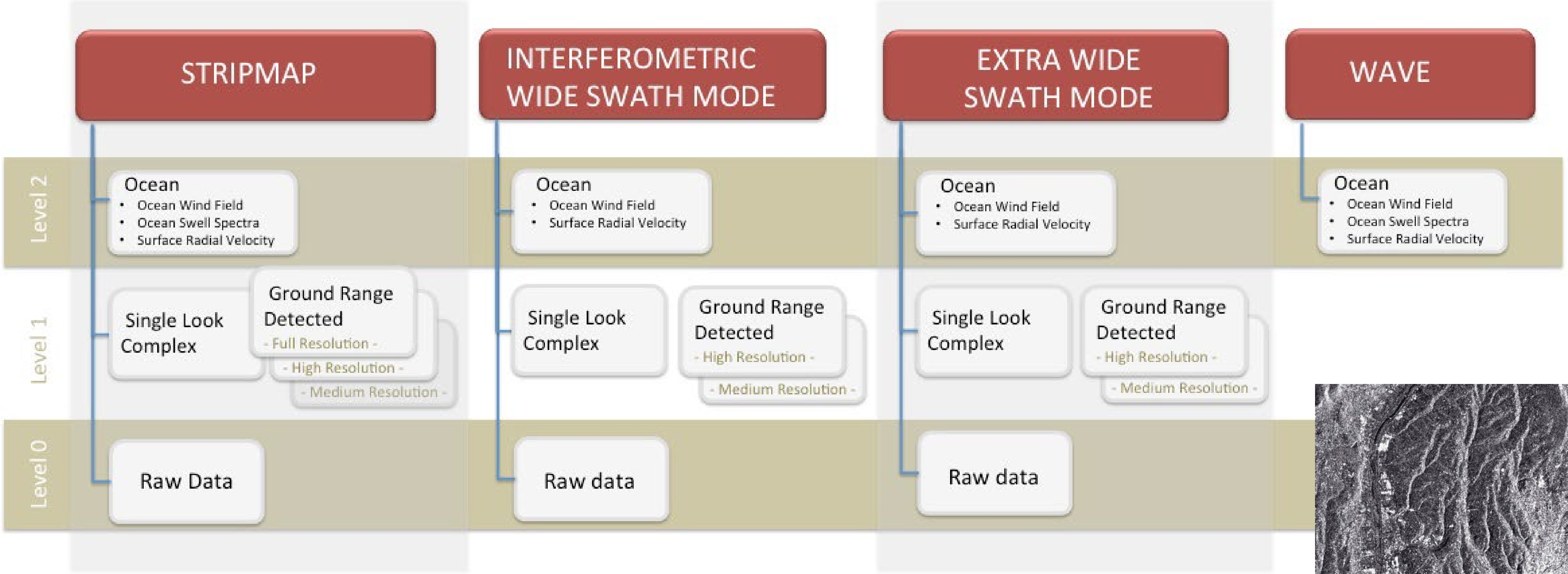
New Applications

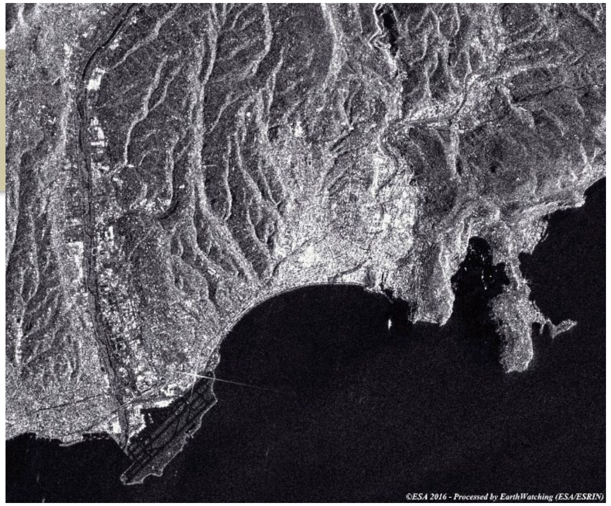
“Cognitive” Microwave Instruments – is it worth?

Cognitive Capabilities can in principle be applied to a range of spaceborne microwave instruments potentially enabling new applications, with potential advantages on latency, performance, system sizing, operations:

- **Synthetic Aperture Radars**
  - E.g. fast-responding tip-and-cue SAR cognitive system identifying and tracking moving icebergs, or ships, or any other objects of interest (e.g. classification/segmentation,...)
- **Microwave Radiometers**
  - E.g. fast-responding tip-and-cue Atmospheric Radiometer identifying critical atmospheric phenomena, and then observing it at higher resolution and integration time, for better scientific return
  - E.g. real-time flagging and classification of RFI, then reconfiguring in real-time for RFI mitigation
- **Weather (Precipitation/Rain) Radars**
  - E.g. fast-responding tip-and-cue Atmospheric Radiometer identifying critical atmospheric phenomena, and then observing it at higher resolution and accuracy for better weather forecast
- **Radar Altimeters**
  - E.g. tip-and-cue Radar Altimeter identifying certain SSH mesoscale phenomena or catastrophic events

SAR Data – Sentinel-1 Example

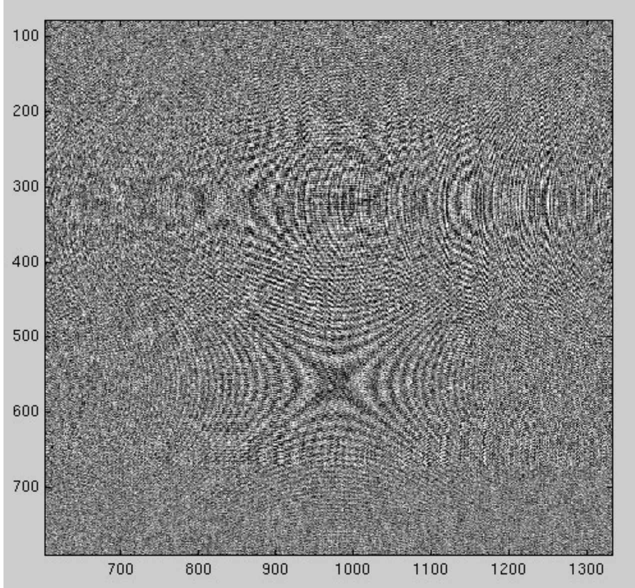




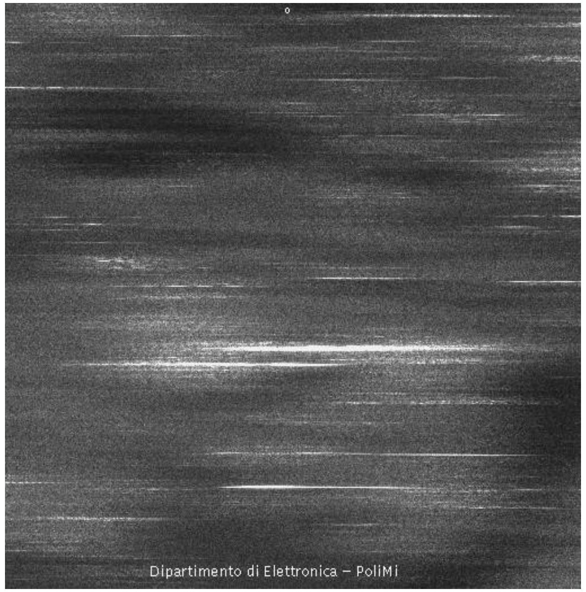
Sentinels Data Products List and Sentinel-1 Image of Nice, France

SAR Image formation processing stages

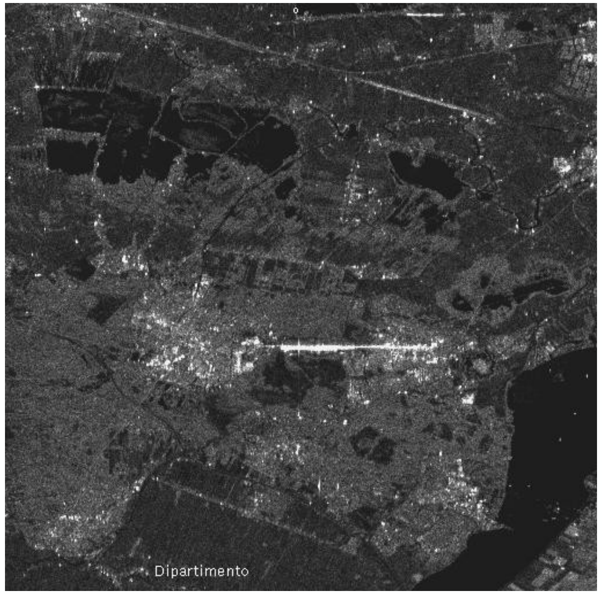
Raw SAR Data



Range Compressed Data



SAR image



Range Compression → Azimuth Compression

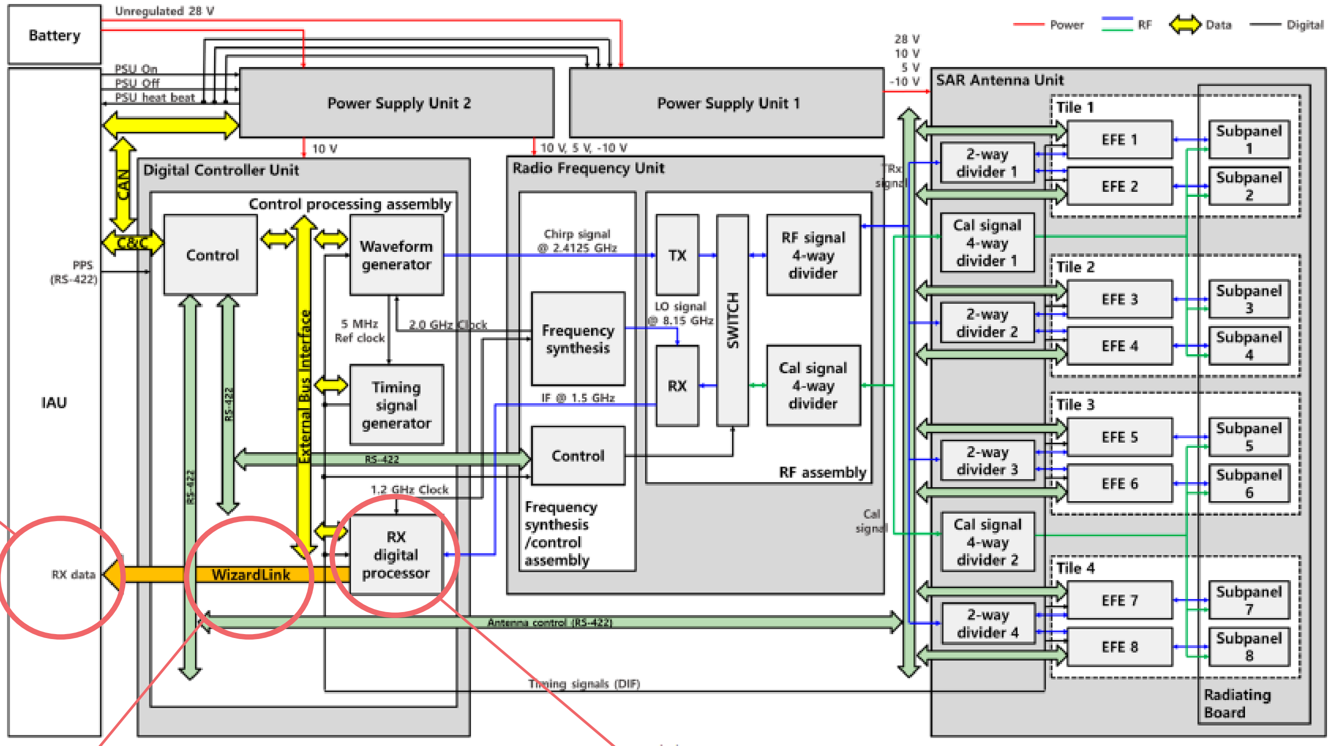
SAR Digital Controller Unit – Payload architecture

Processed L0

Interfacing MMU or OBP

On-board processor

L0



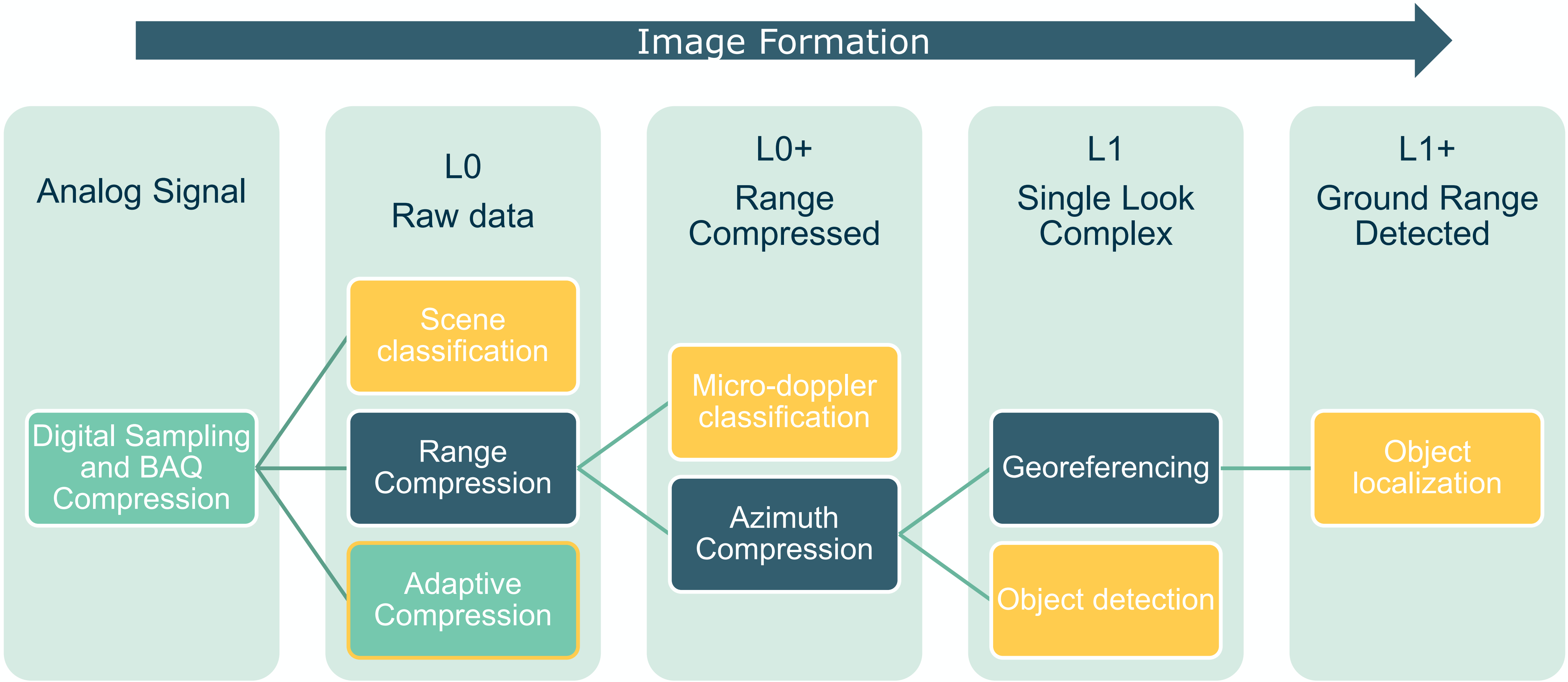
Quantized L0

Processing within the Digital Controller Unit

Uncompressed L0

New interfaces on Digital Processor Module

SAR On-board data processing



Machine learning can be applied to different image formation stage

SAR Data driven algorithms – Working areas

Uncompressed Raw data — L0

Currently data only synthetic/simulated

- *Improvement of data compression*
- *Processing on full precision data*

Optimized Compression

Raw Data
~500-5000 Mbit/s

Quantized Raw data — L0+

Data can be decoded from Sentinel-1 L0

- Efficient Single-Look Complex focusing of data
- Data prioritization without SLC
- Real time beam steering
- Micro-doppler analysis

Raw classification

On-board formed image data — L1

Data can be formed from Sentinel-1 L0

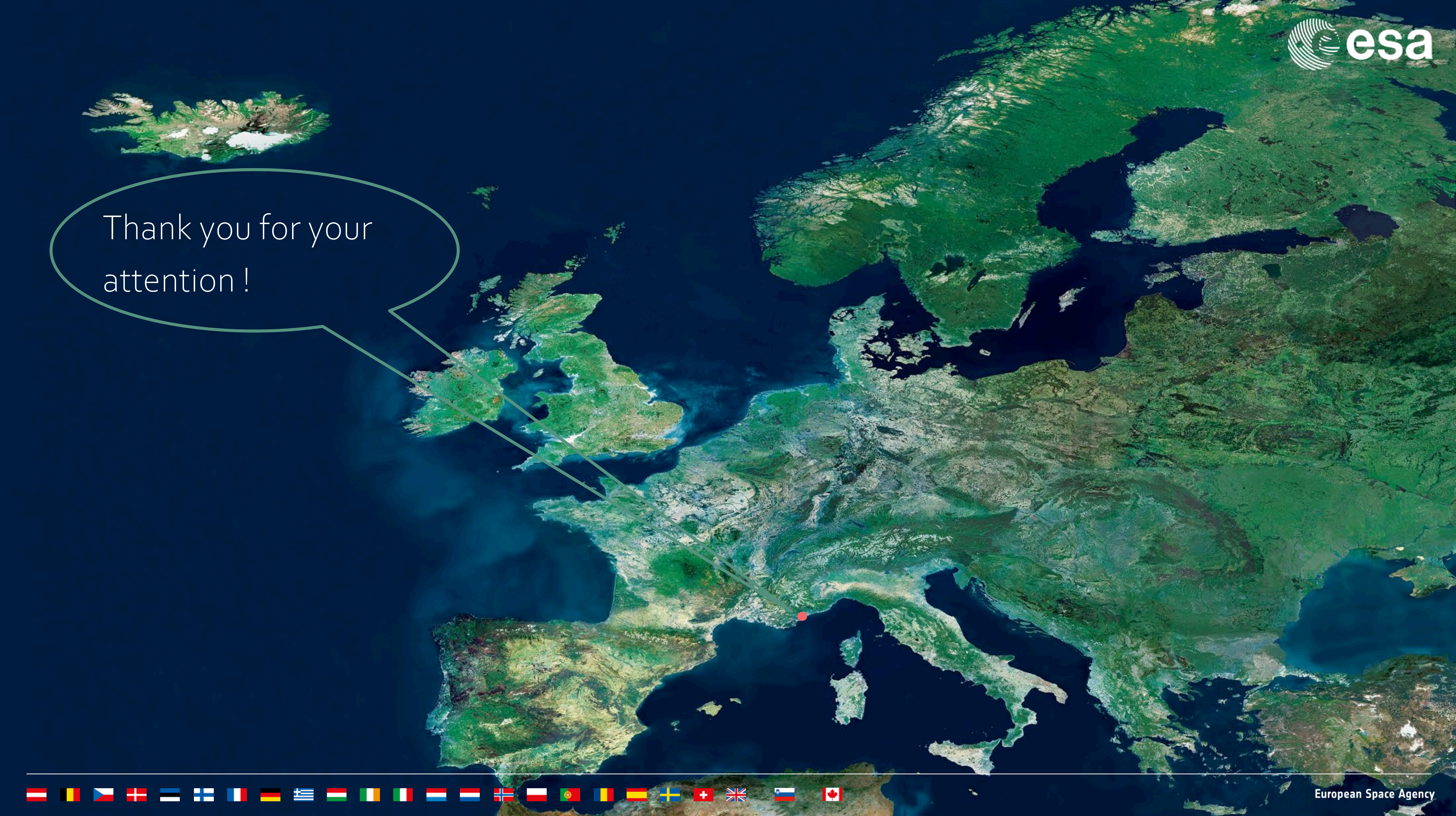
- *Patch Segmentation*
- *Object Detection*
- *Tasking*

Image formation

CNN inference*
~3-30 Mbit/s
~1-10 Mbit/W

"Science on-board"? — L2

*ZCU102


Thank you for your attention !
esa
European Space Agency

Q/A