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CENTRE NATIONAL D'ÉTUDES SPATIALES

FLIGHT SOFTWARE, NETWORK STACK & SIMULATOR FOR SWARMS OF SATELLITES

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SWARM
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– OCTOBER 2025 –

AGENDA

SWARM MISSIONS

Increasing new missions concepts with multi-satellites collaborating (mothership centered up to completely fair)

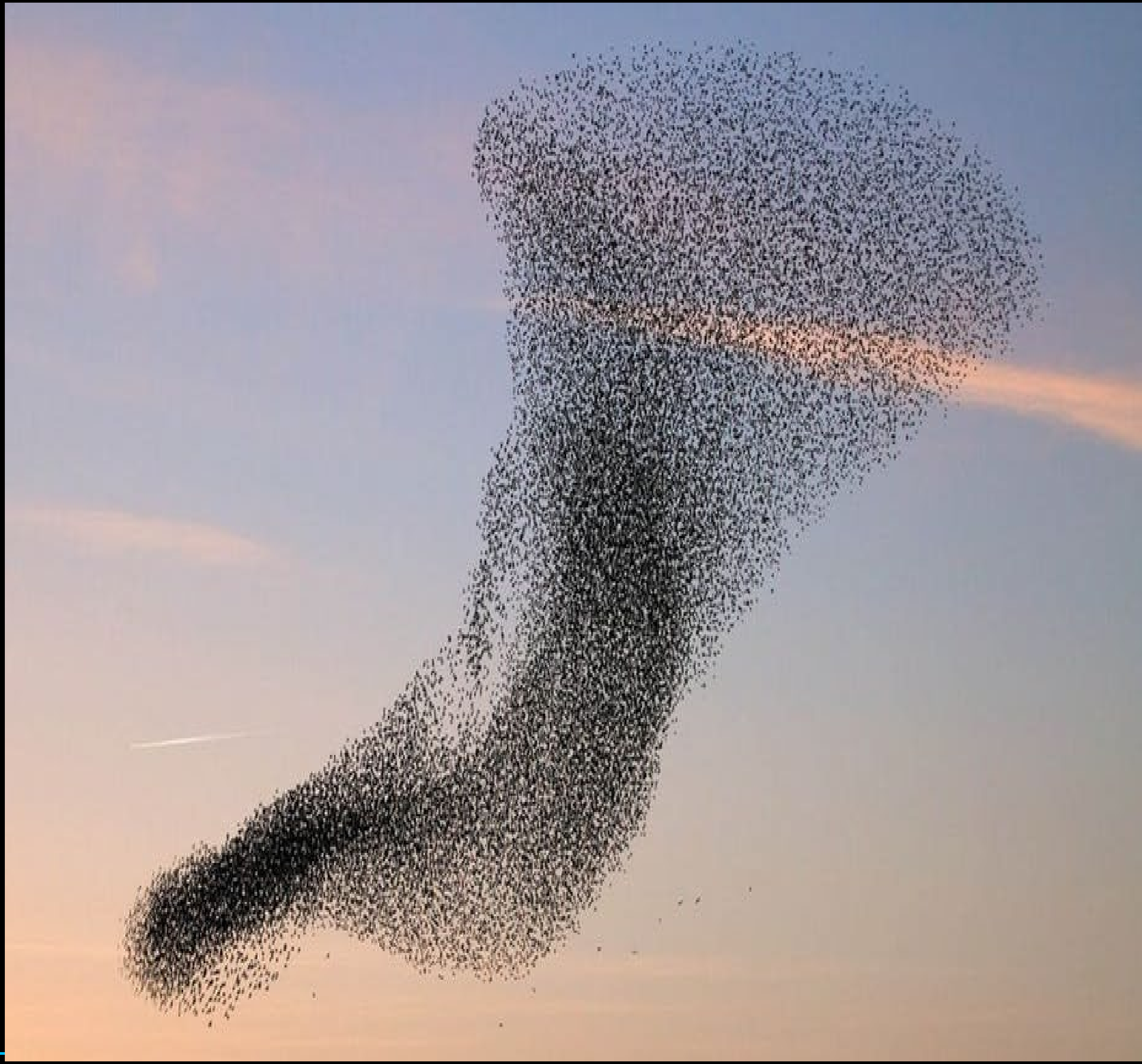
From 3 to 50+ satellites

Either LEO, GEO, lunar, asteroids or interplanetary centered

Aim at constituting large scale distributed instruments (multi-point measurements such as interferometry, …)

Acting following a collective scheme and managed as a single object

High level of autonomy, resilience, with auto-reconfiguration capabilities



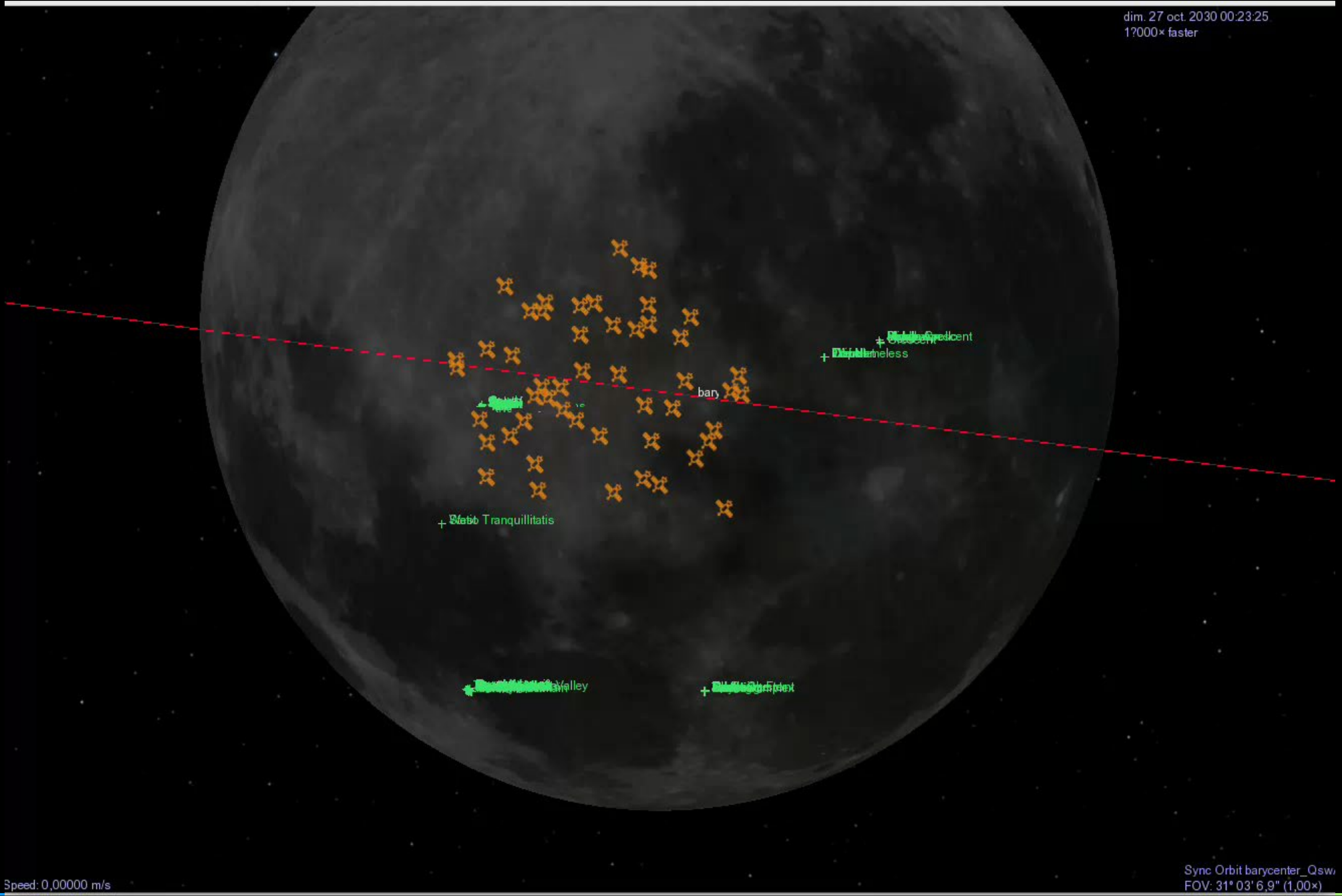
02

IDENTIFY AND INCREASE TRL ON MAJOR BUILDING BLOCKS

SWARM MISSIONS – ARE WE READY ?

New challenges at Software level on the following topics :

- Interconnecting ISL, TTC, intra-sat networks
- Swarm autonomy wrt Flight Dynamics functions
- System resilience
- Distribution :
  - Collaboration of functions across the swarm
  - How to design at SW level one distributed payload ?
- How to manage such a system from the Ground ?



* Typical « pulsed » orbits for NOIRE mission courtesy from E. Rouille, LESIA

03

FSW ARCHITECTURE AND TEST ENVIRONMENT

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AVIONICS / FLIGHT SOFTWARE ARCHITECTURE – SWARM MISSIONS

Logical view

Unique at satellite level

Unique at computer level: XNG, KOSMOS

Legacy functions: MASSMEM, THERM, GNSS, AOCS, TTC, Power, TMHD, FDIR sat, M&C, PL

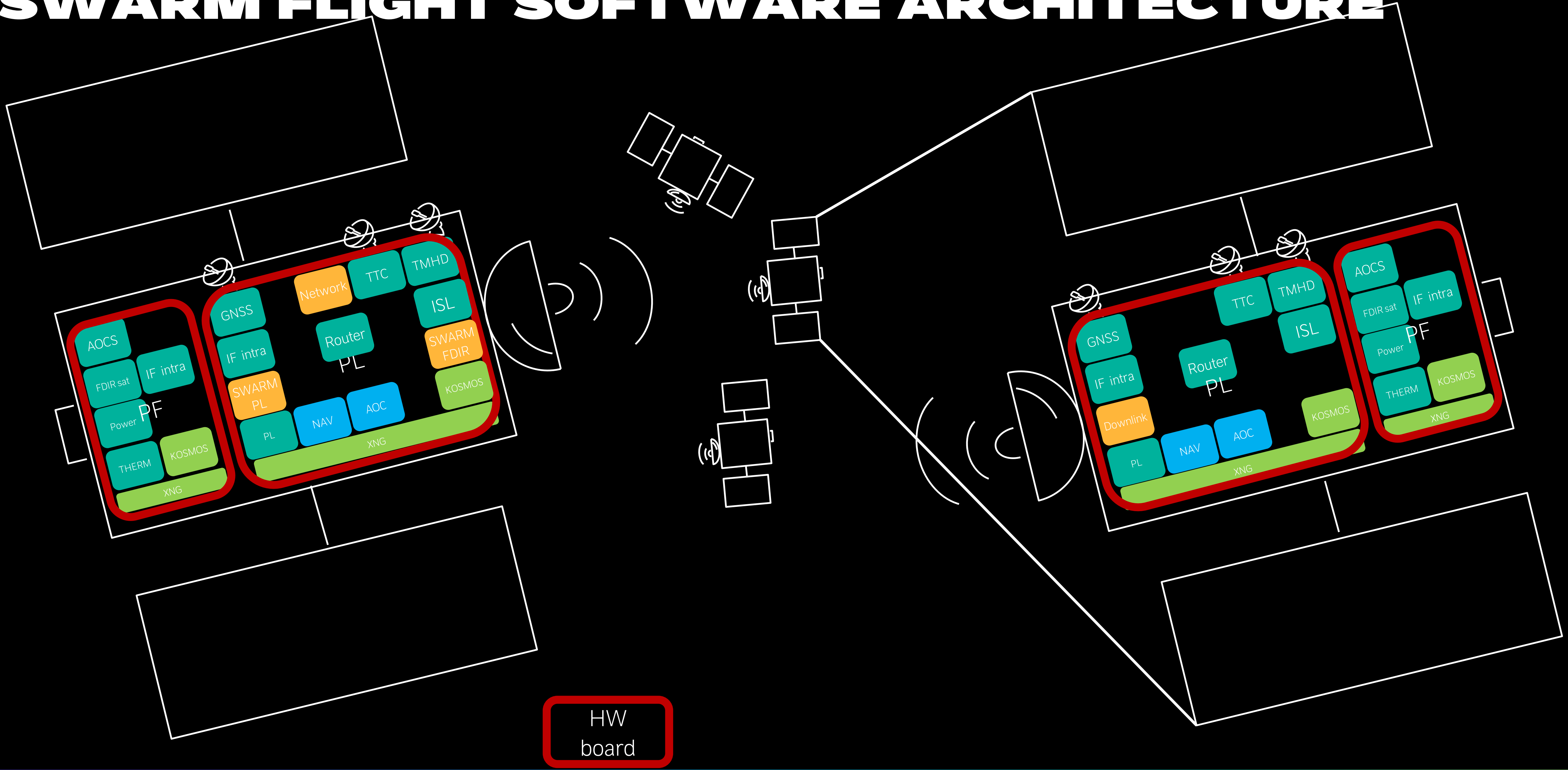
New communication functions: ISL, Router

New autonomy functions: NAV, AOC

Unique at swarm level

Network, FDIR swarm, AOC swarm, PL swarm, Downlink

SWARM FLIGHT SOFTWARE ARCHITECTURE



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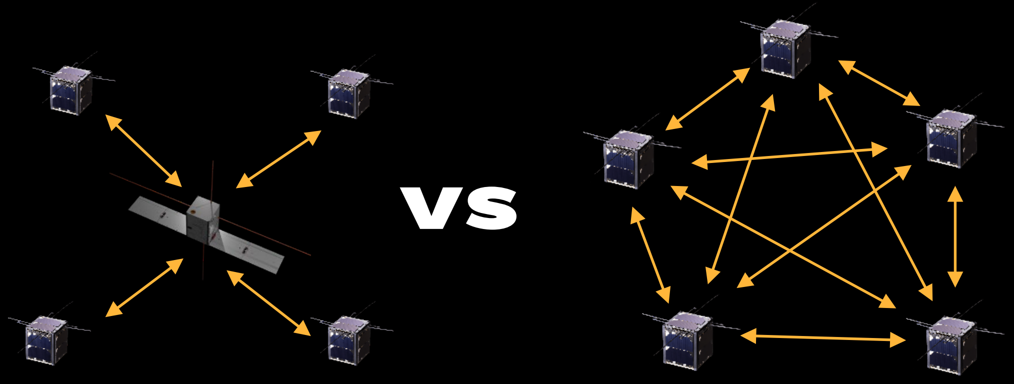
04

NETWORK CONCERNS

ISL CONCERNS

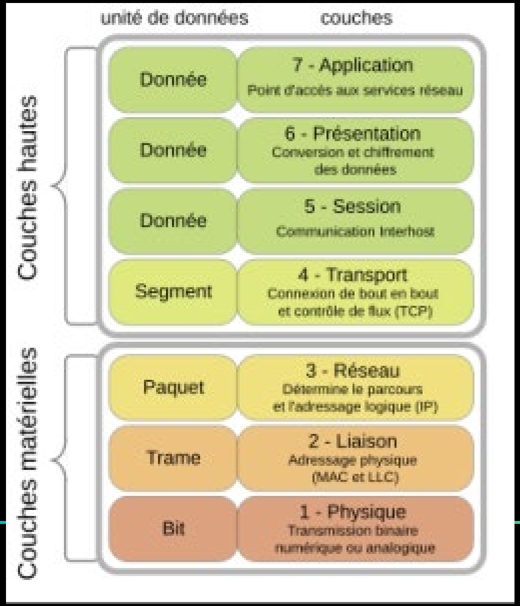


The most dimensioning enabler for swarm missions

- Technology (omnidirectional antenna vs directive links, RF vs optical)
- Topology of the network : full duplex, FDMA/TDMA/CDMA, point to point, 1 to n, n to n, bandwidth ?
- Usable for ranging and collective time when no GNSS is usable ?

⇒

- Decouple this physical layer / datalink function as much as possible from the others (follow the OSI approach !)
- Adapt easily the ISL properties on the simulator
- Unicast, multicast, broadcast
- Proof of concepts for ranging, GNSS messages diffusion, TC relay across the swarm

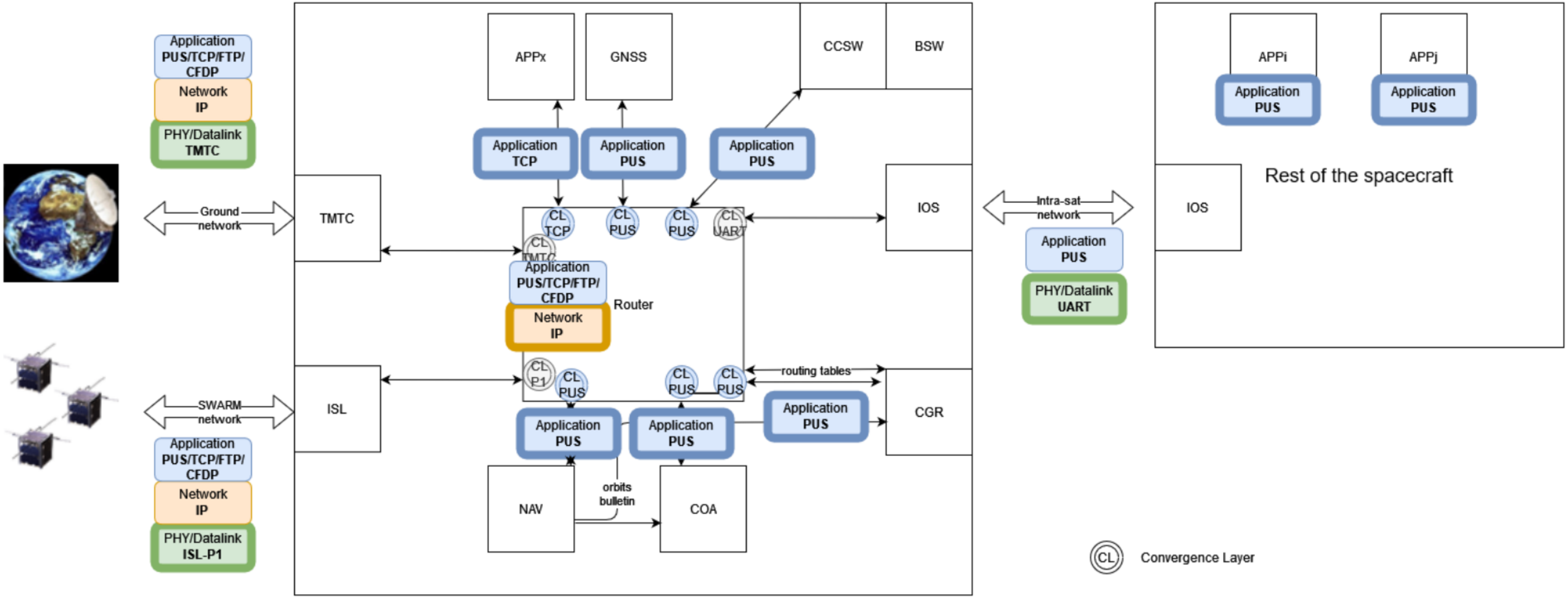


Application
PUS/TCP/FTP/CFDP/…

Network
IP

PHY/Datalink
TMTC or P-1 or UART

SWARM NETWORK STACK



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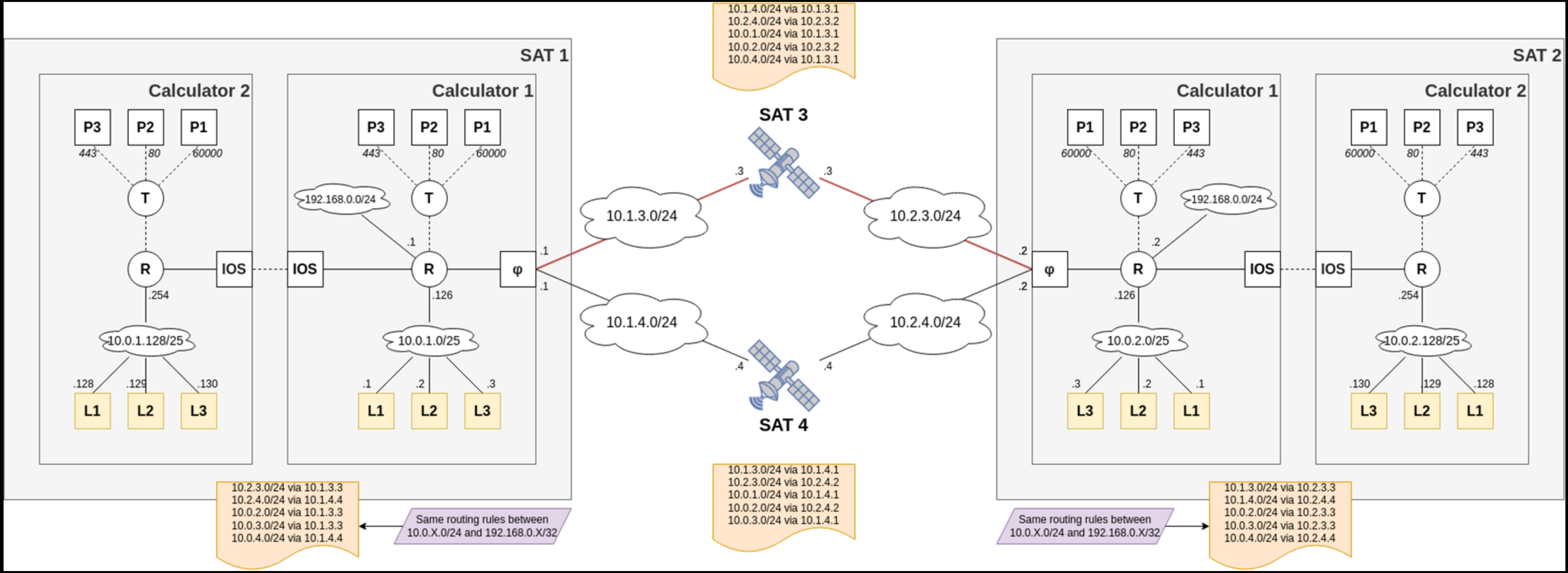
SWARM NETWORK STACK

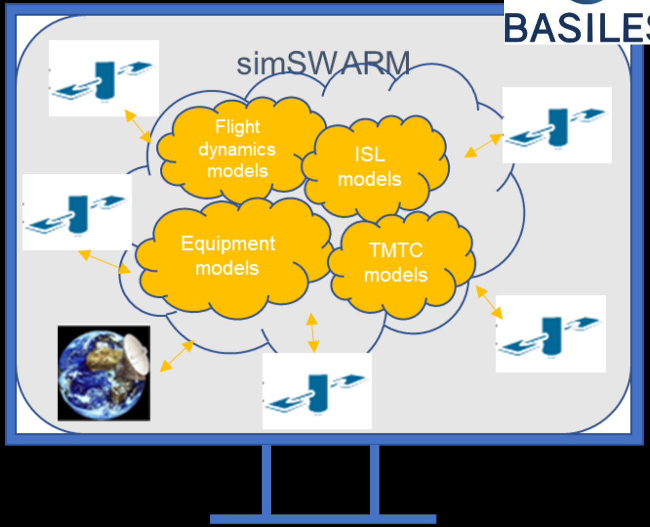


SWARM TEST BENCH - 2 CONFIGURATIONS

1 simulator

Discrete-event simulation infrastructure, SMP/SMP2 simulation standard

Chaining models into a simulator, including flight software

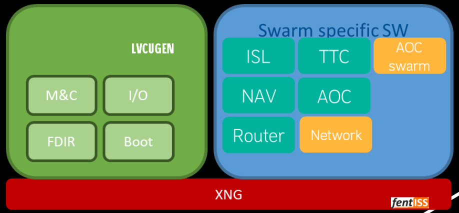


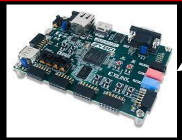
2 configurations

PIL

Processor in the loop – 1 HW board for each computer

TTC and ISL links managed through UART links



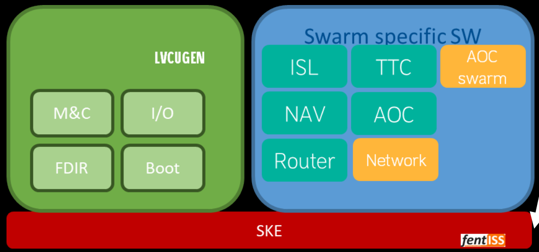


Used for mono-satellite tests with stubbed neighbours – no scalability

Full simulated

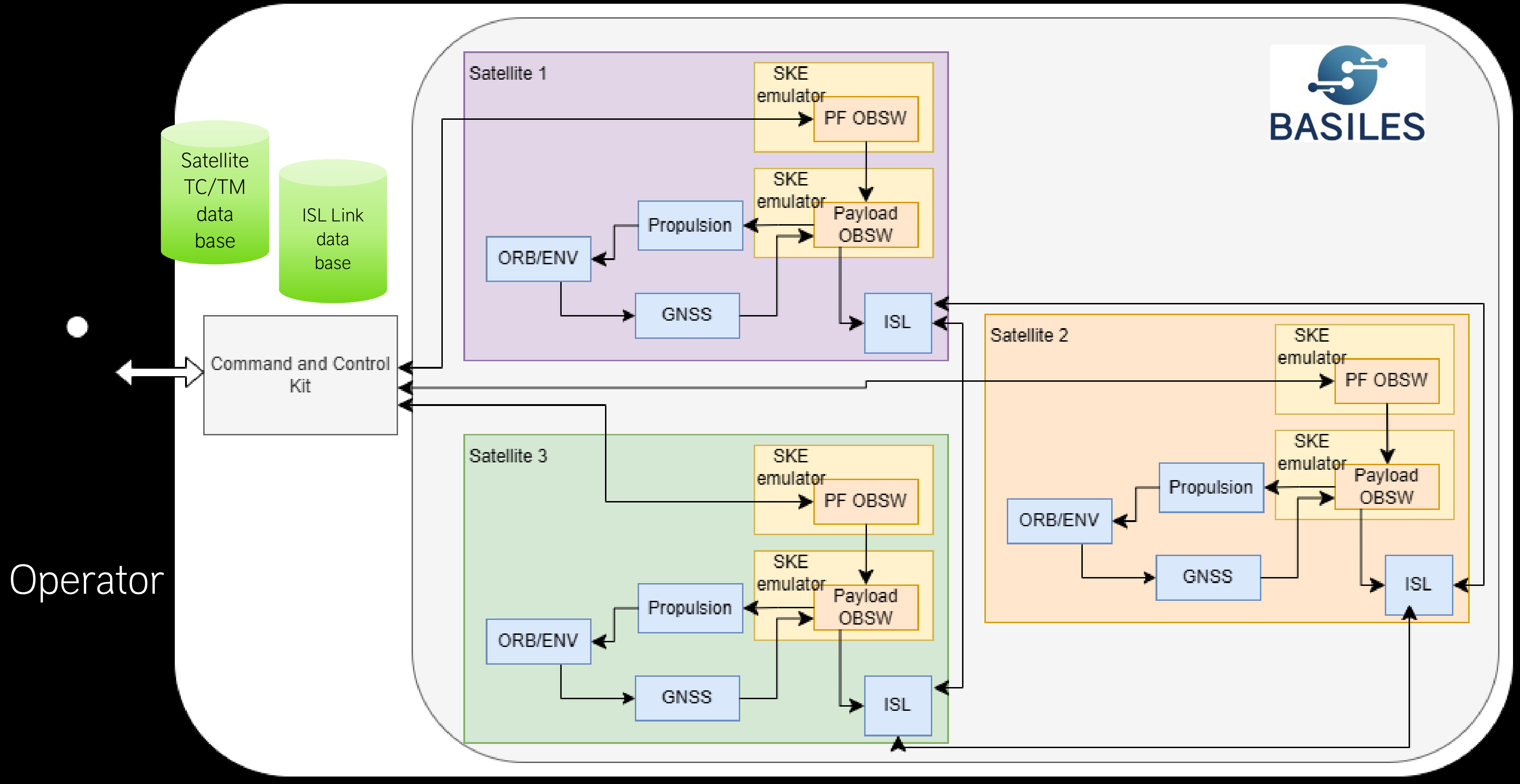
FSW running as a model thanks to a XNG-A653 emulator that enables to run FSW partitions on Linux – compiled with the host compiler

TTC and ISL links managed through A653 ports



Used for system tests, with each satellite running the real FSW simulated – easily scalable

SWARM TEST BENCH – OVERALL VIEW




```
Every 1.0s: ps -eo psr,pcpu,pmem,cmd --sort=-pcpu | grep ske tu-apis-p01.cst.cnes.fr: Mon Sep 2

 11 21.4  0.1 ske_bsl_standalone 90 91
 42 21.2  0.1 ske_bsl_standalone 109 110
 24 21.1  0.1 ske_bsl_standalone 71 72
 17  9.5  0.0 nav-xng_ske-debug.elf
 32  9.5  0.0 nav-xng_ske-debug.elf
 28  9.5  0.0 nav-xng_ske-debug.elf
 33  4.5  0.0 apppus-xng_ske-debug.elf
 43  4.5  0.0 apppus-xng_ske-debug.elf
 15  4.5  0.0 apppus-xng_ske-debug.elf
 46  4.0  0.0 isl-xng_ske-debug.elf
 27  4.0  0.0 isl-xng_ske-debug.elf
 36  4.0  0.0 isl-xng_ske-debug.elf
 26  3.9  0.0 rap-xng_ske-debug.elf
  5  3.9  0.0 rap-xng_ske-debug.elf
 23  3.9  0.0 rap-xng_ske-debug.elf
 37  3.5  0.0 instrum-xng_ske-debug.elf
  5  3.5  0.0 instrum-xng_ske-debug.elf
 40  3.5  0.0 instrum-xng_ske-debug.elf
 41  3.4  0.1 ske_bsl_standalone 74 75
  6  3.4  0.1 ske_bsl_standalone 93 94
 45  3.4  0.1 ske_bsl_standalone 112 113
 12  3.1  0.0 ccsw-xng_ske-debug.elf
  5  3.1  0.0 ccsw-xng_ske-debug.elf
  7  3.1  0.0 ccsw-xng_ske-debug.elf
 18  3.1  0.0 router-xng_ske-debug.elf
 29  3.0  0.0 router-xng_ske-debug.elf
 23  3.0  0.0 router-xng_ske-debug.elf
 21  2.9  0.0 gnss-xng_ske-debug.elf
 14  2.9  0.0 gnss-xng_ske-debug.elf
  2  2.9  0.0 gnss-xng_ske-debug.elf
 26  2.6  0.0 ios-xng_ske-debug.elf
 32  2.6  0.0 ios-xng_ske-debug.elf
```

EQUIPEMENT FUNCTIONAL SIMULATIONS ENVIRONMENT

GNSS simulation

- Real GNSS constellation data (GPS, BEIDOU, GNSS) retreived on the net.
- GNSS receiver simulated for each satellite :
  - Based on Patrius (CNES generic Flight Dynamics Library)
  - Simulated CODE, PHASE measures for each emittor
  - Simulates a table of n tracked GNSS emittors

Functionnal Propulsion : DeltaV, direction, noise

Inter-Satellite Link :

- Data rate = function of (SNR for each couple of satellites, distance, …)
- Inter-satelllite messages emission commutation/decommutation capacities in the simulator
- Broadcast, Unicast messages, …

Environment/Orbit simulation

- Precise
- Based on Patrius
- Environment : simulation of tidal forces/atmospheric density/earth gravity up to high orders/Sun and moon Gravity/Radiation pressures of solar irradiance + integrator

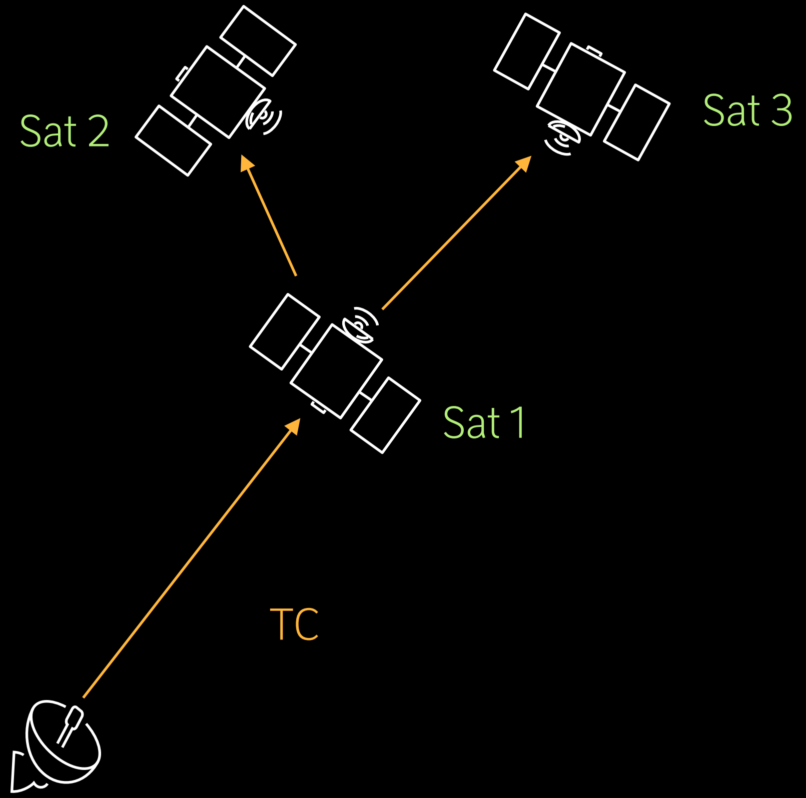
Theoretical Attittude simulation

- Geocentric

Command/control Kit

- Using generic TC/TM kits
- 2 data bases for com/decom

SWARM SYSTEM TESTS

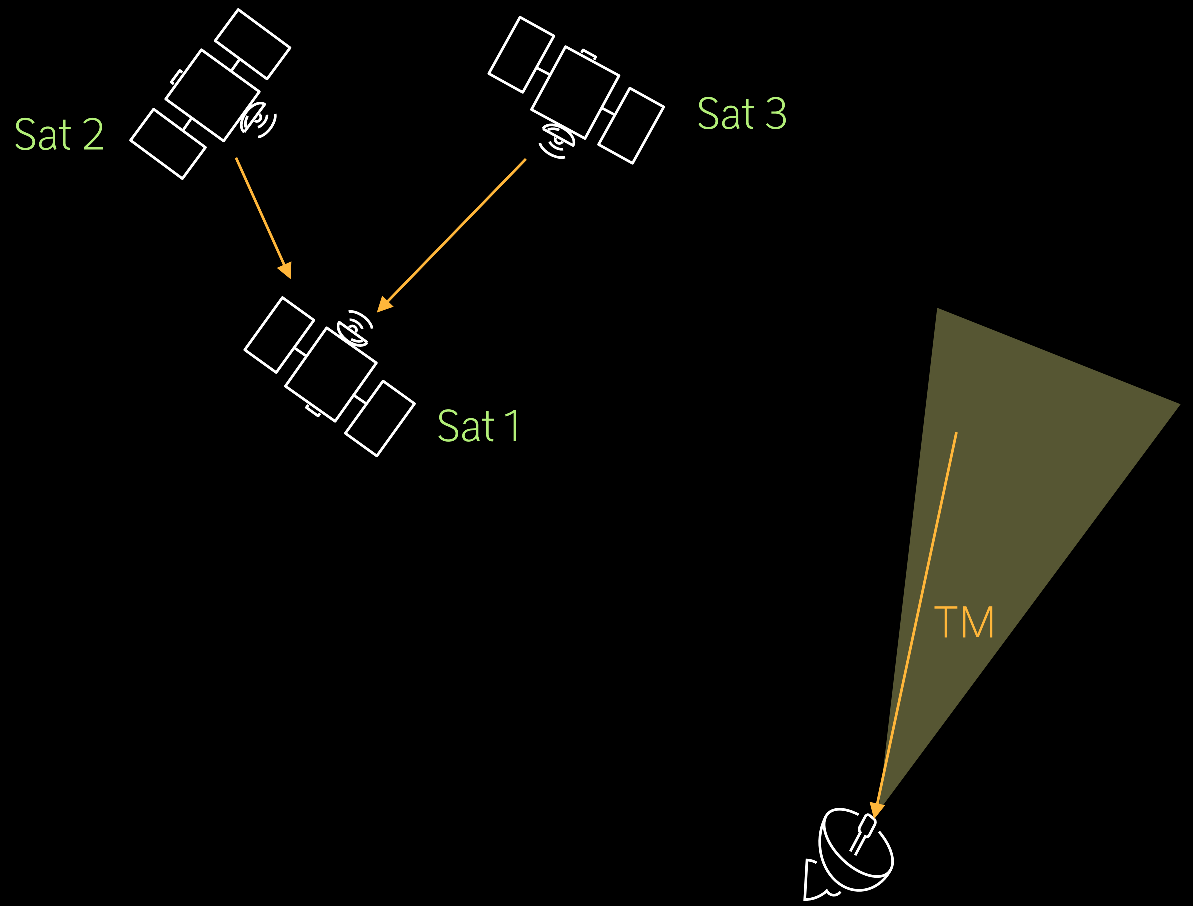


Use case 1 : sat 1 relay between ground and 2 other satellites

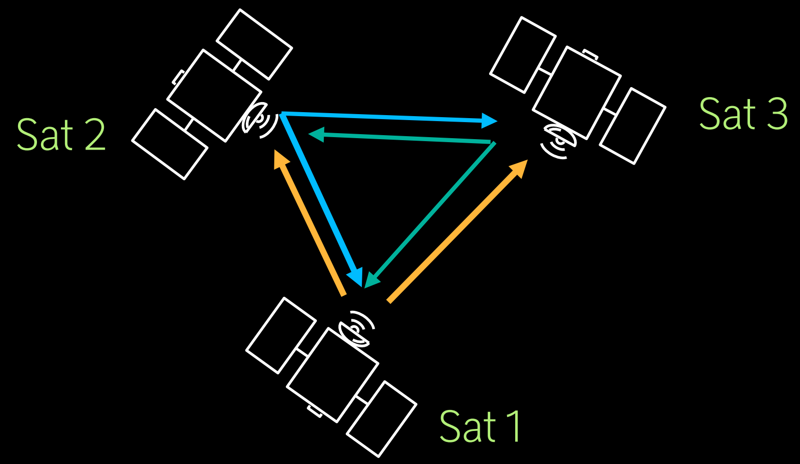
SWARM SYSTEM TESTS

Use case 2 : sat 1 relay between 2 other satellites and ground

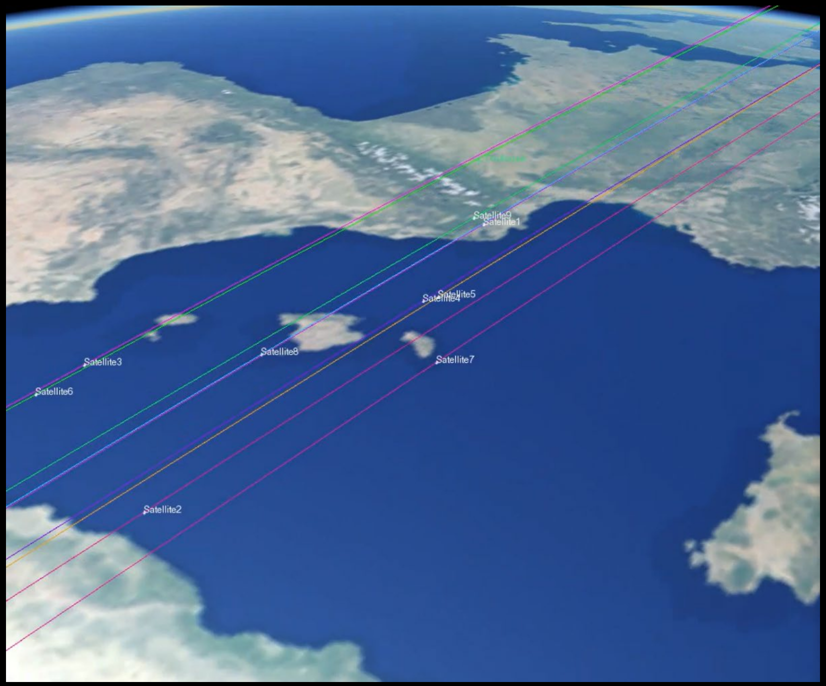
If No visibility : data storage



SWARM SYSTEM TESTS



Use case 3 : navigation data exchange between satellites
Broadcast mode



STATUS AND WAY FORWARD

- First versions of the simulator and FSW with representative orbits and ISL models
- Firsts demonstrations including routing, ranging and flooding protocol successful with:
  - 3 satellites
  - 20 satellites
- Network stack implementation on going
- New Flight Dynamics functions on going
- … then swarm distributed system functions
- Promising performances of the simulator to run the swarm with an appreciable functional representativity

- This simulator aims at being tuned according to new missions specificities