ELECTRONICS & DEFENSE

A WR based implementation of Coherent Clock

NAVISP Final Presentation: 29/04/26

Contract number: C4000142450 of NAVISP EL2-174

NAVISP2-PPT-SEDS-174-00019

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Agenda

Chapter 01

Project Introduction

Background & Motivation

GNSS provides high performance PNT:
- ✓ High accuracy
- ✗ Vulnerable to jamming, spoofing & multipath environments

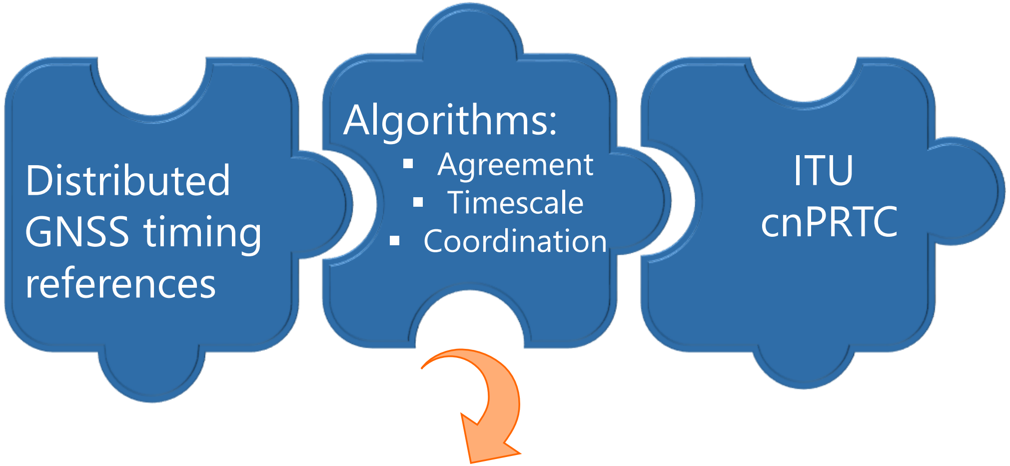
Modern **Global Critical Infrastructures** depend on precise and robust timing.

Emerging 5G/5G-advanced Applications demand new requirements:
- Tight timing accuracy
- Phase alignment
- Robustness & security

Precise & Robust Timing

Coherent, network-wide coordinated clock:
- Resilient & Traceable
- Sub-nanosecond accurate Timing Service for GCI

Project Concept



ESA Coherent Clock Proof of Concept:

- **WR Sub-nanosecond inter-node synchronisation.**
- **Seamless failover between GNSS references.**
- **Continuous cross-validation among timing sources.**
- **Robustness against GNSS disruptions.**
- **Highly scalable operation across large networks.**

Objectives at Project Kick-off Vs Project Results

Project Objectives defined at KOM:

- ✅ Define use-cases and system requirements for a WR-based coherent timing service applicable to Global Critical Infrastructures (GCI).
- ✅ Implement the agreement, timescale, and coordination algorithms within WR devices.
- ✅ Develop laboratory test setups to validate performance under controlled conditions.
- ✅ Deploy and validate the solution in a relevant environment, enabling formal TRL evaluation.
- ✅ Reach TRL 5 at Final Review through end-to-end demonstration in a representative infrastructure environment.

Main Project Results:

- ✅ Demonstration of the **technical feasibility** of a distributed, coordinated timing solution.
- ✅ Consistent Performance with sub-nanosecond WR-PTP distribution.
- ✅ Proved **robust behaviour** under clock anomalies.
- ✅ Fully integrated software stack ready for deployment testing in GCIs.
- ✅ Successful demonstration of the complete system in a laboratory environment and a relevant environment, reaching **TRL5**.
- ✅ Solid foundation for future work, ensuring alignment with organisational priorities and stakeholder expectations.

Chapter 02

State of the Art and Use Cases

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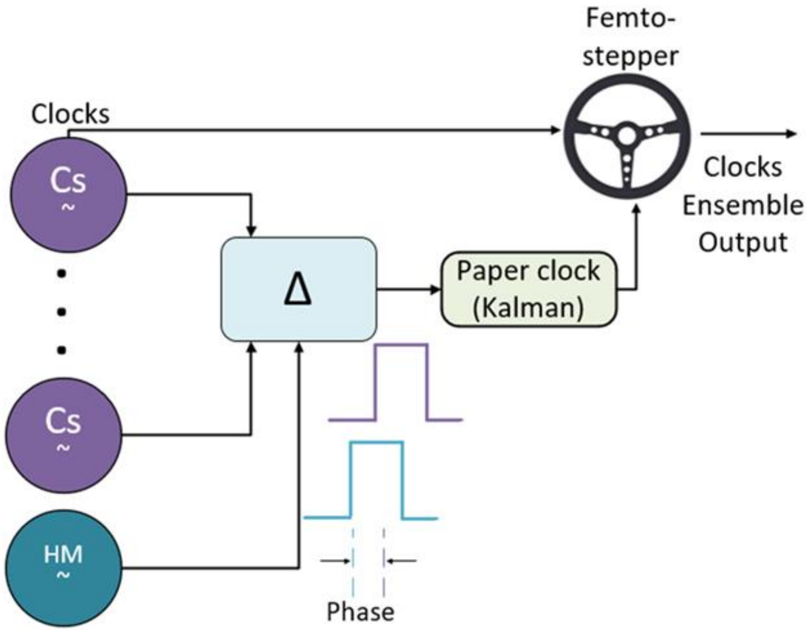
Introduction

- **Timescale**: is a standardised and continuous sequence of time, established to provide a common reference for timekeeping. Essential for GNSS, telecoms and science.

- **Clock ensemble:** Group of clocks combined to improve time accuracy and stability. Performance criteria:
  - **Stability:** Consistency over time
  - **Accuracy:** Closeness to true time
  - **Robustness:** Tolerance to clock failures

- **Coherent clock:** Distributed Clock Ensemble for Telecom.

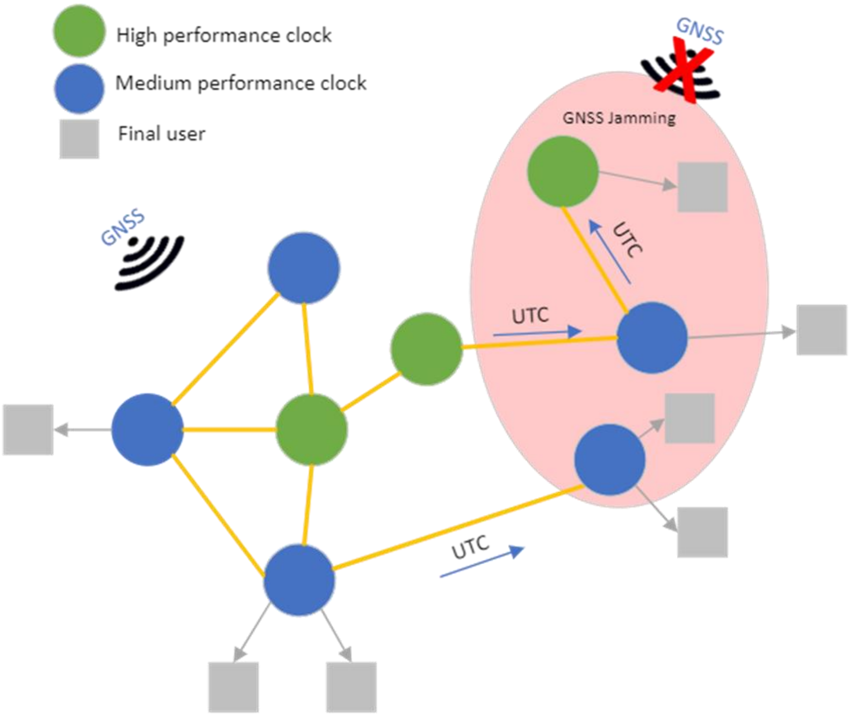


Why: Motivation of distributed clock ensemble

- Increase **resiliency** and **performance**. Allow more clocks available in the ensemble.
  - Provide responsiveness to GNSS disruptions.
  - Run multiple timescale algorithms in parallel
  - Timescales algorithms for hybrid clocks: GNSS, Rubidium, Caesium, Maser.
  - Fast mitigation of phase and frequency jumps.
- **Mesh network**: Without specific Grand Master dependency.
- Standard protocol: **WhiteRabbit** (PTP-HA (IEEE-1588-2019)).
- Ultra-accurate time distribution (from sub-ns to tens of ps).
- Distribute solution to fill gap between Rubidium and Caesium/Maser.
- Phase noise will depend on local clock while long-term stability in clock ensemble.

Where: Use cases

- Critical infrastructure:
  - National time scale
  - Telecom
    - National rings (cnPRTC)
    - Regional rings (Rubidium)
  - Inter-Datacenters
- Space
  - GNSS Ground segment
  - Inter satellites (LEO/MEO)
- Defense
  - Swarm of UAV
  - Naval fleet
  - Etc.



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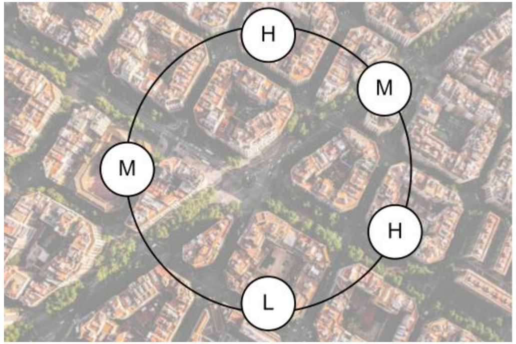
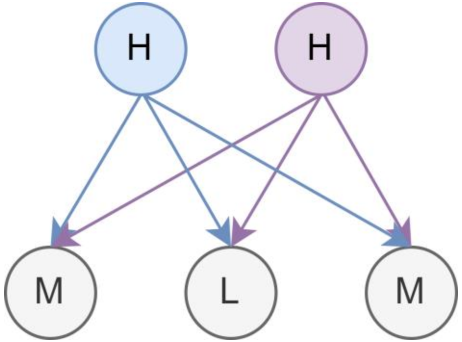
Studied Use-Cases

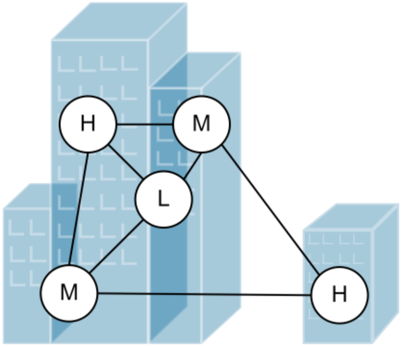
- **Ring network**
  - Communications



- **Clock hierarchical network**
  - Enterprise, scientifics



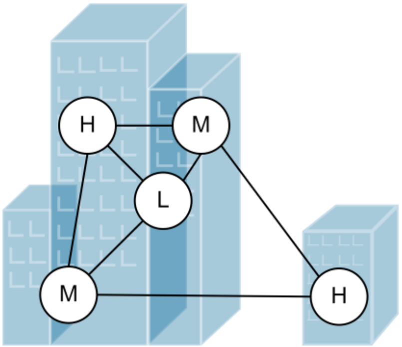
- **Mesh network**
  - Multipurpose

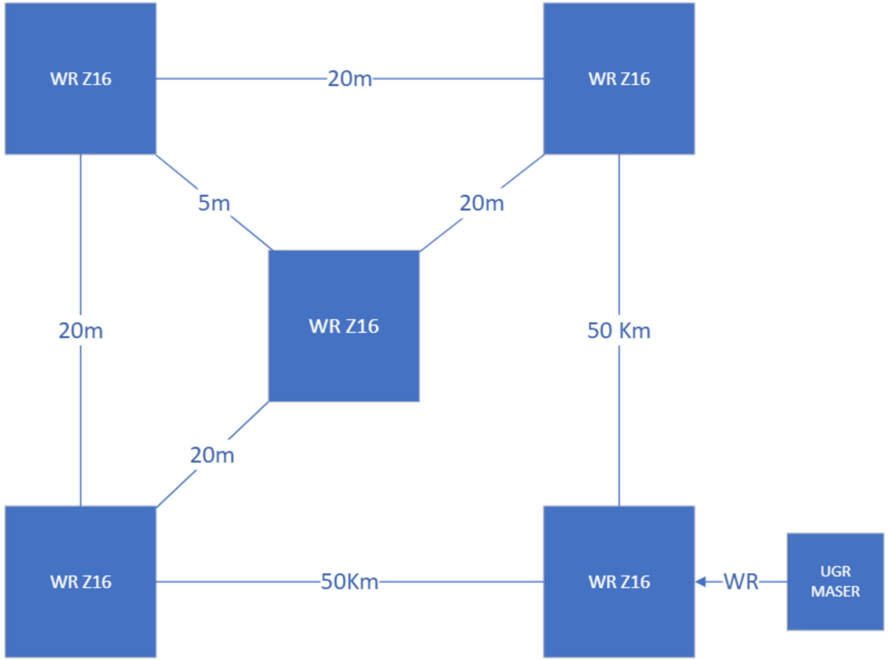


	Clock type	Price
H (High performance)	Cesium AC, Maser AC	>50k €
M (Medium performance)	Rubidium AC, OCXO (high performance)	500€ - 5000€
L (Low performance)	VCXO	<100€

Selected Use-Case

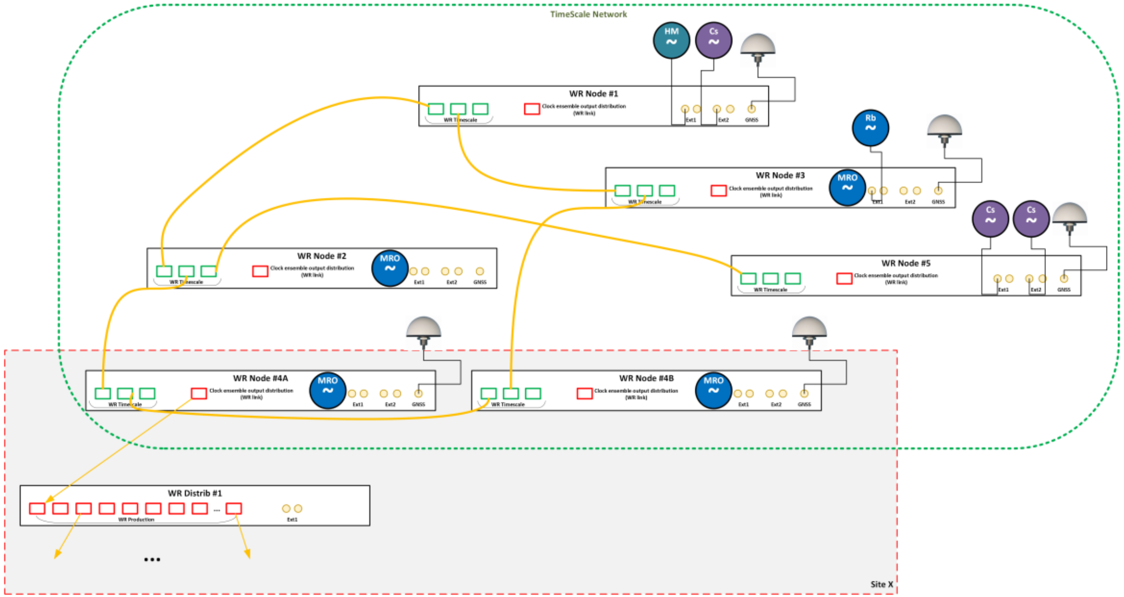
- **Mesh network**
  - Topology





Generic WR Network

- **Ensemble Network:**
  - Clocks connected to produce an ensemble clock.
- **Distribution Network:**
  - Physical 10MHz 1PPS output.
- **Cost-Effective Solution:**
  - FPGA-based
  - Rubidium Clock



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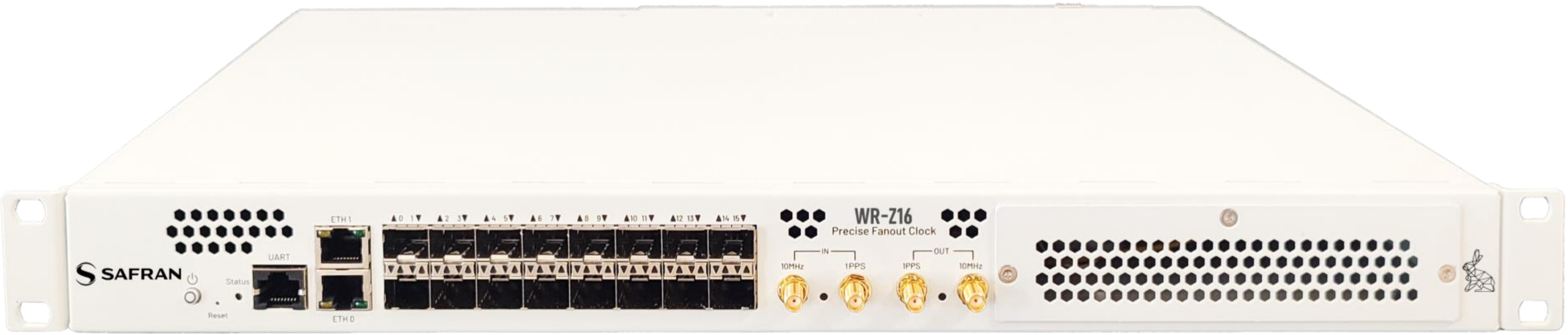
Nodes: WR-Z16 LJ unit

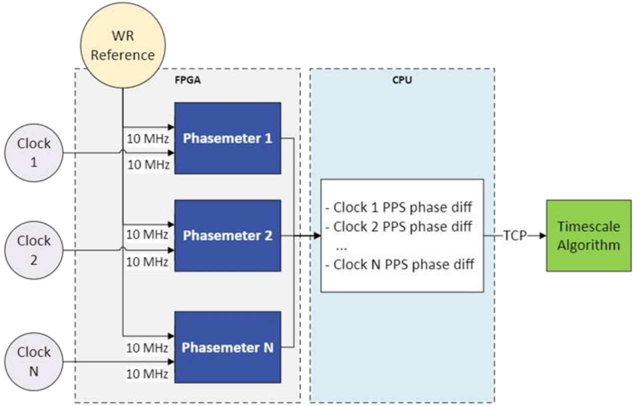
- **WR Z16**
  - Up to 3 slaves
  - 2 SMA inputs (10MHz or PPS)
  - 1 Clock output (10MHz and 1PPS)
  - 1 Mosaic-T GNSS receiver.

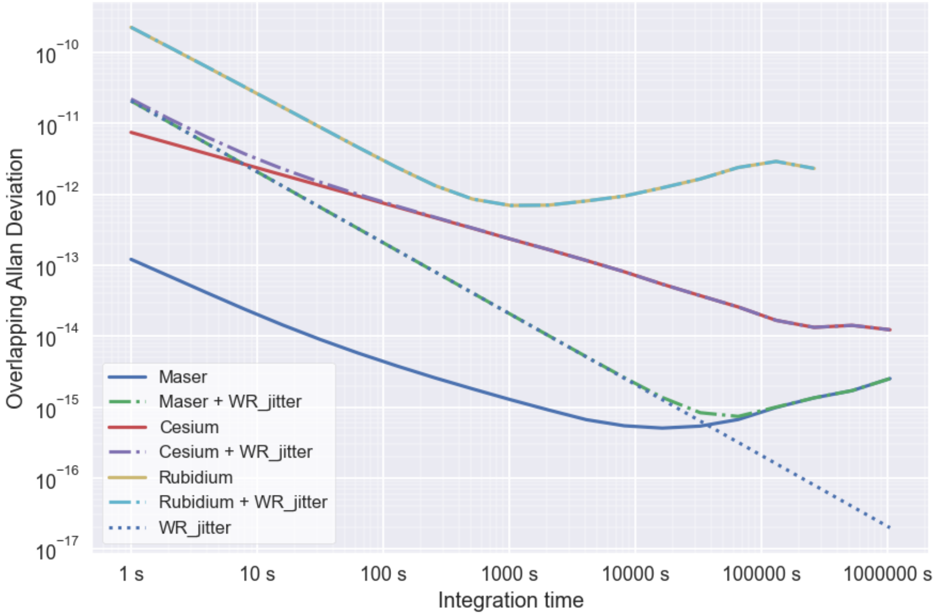


[White Rabbit Z16 - Safran - Navigation & Timing]

WR-Z16 as cost effective solution

- Use **Rubidium clocks**:
  - WhiteRabbit jitter (12ps) lower than Rubidium clock stability for every integration time
  - Stability with Caesium and Maser Clocks can be seen at longer integration times
- **FPGA PicoStepper** (~18ps/step)
- **FPGA Multichannel Phasemeter**
  - Phase comparator with sub ps resolution.





Chapter 03

Verification and Validation Campaigns

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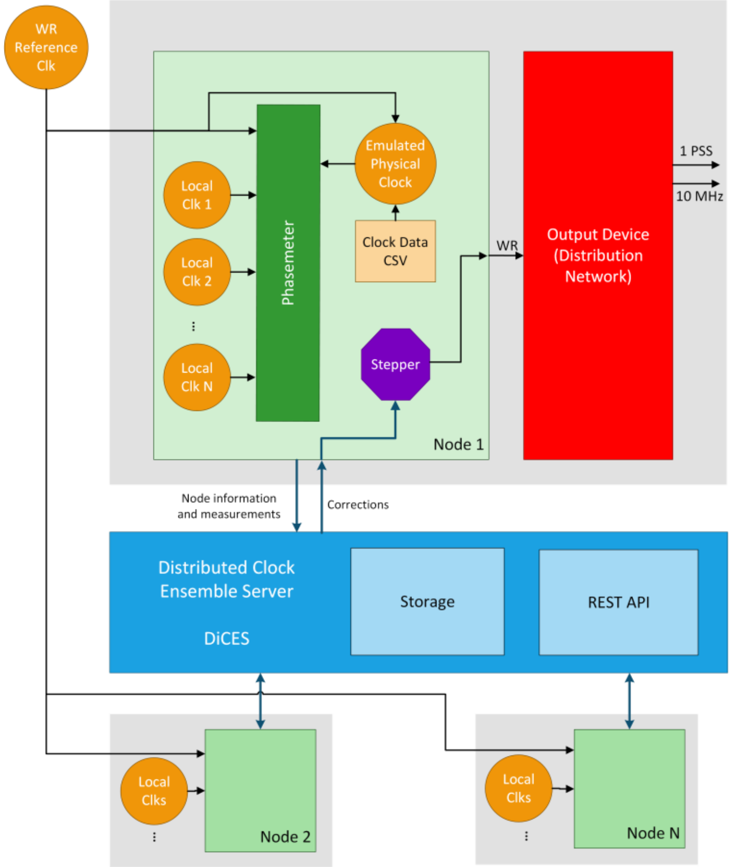
Distributed Clock Ensemble Server: DiCES

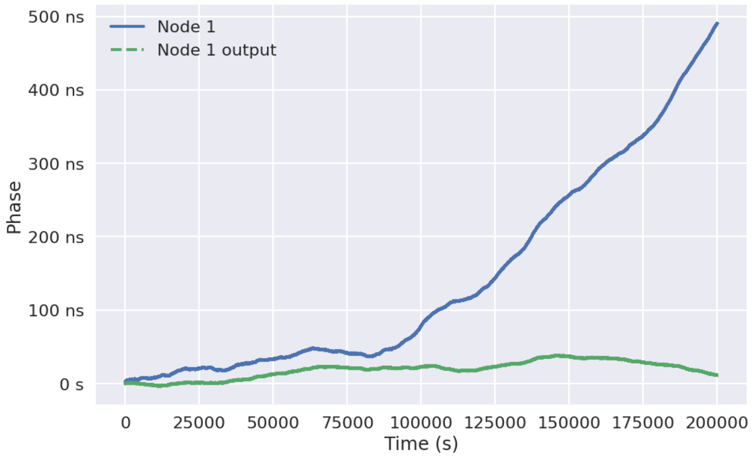
- All nodes communicate with a **server**.
- **Status information** and clock **measurements** from the nodes are received in the DiCES.
- This information is **stored** inside.
- The ensemble clock is **computed**, and each node's correction is delivered. The node is able to apply the corrections and **achieve the ensemble clock**.



Data Collection: DiCES REST API

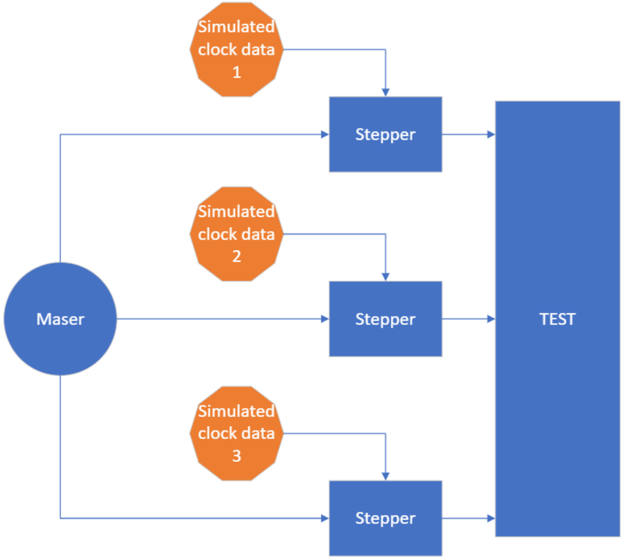
- The DiCES exposes a **REST API** to allow consulting the **status of the node**.
  - GNSS Status.
  - Neighboring nodes.
  - WR Status.
  - Clocks available and their status.
- Historical data about measurements and the internal Kalman information can also be consulted.
  - The information is **timestamped**.
- Ensemble algorithm and other parameters are set through a configuration file.
  - The REST API allows online **manual weight** selection.

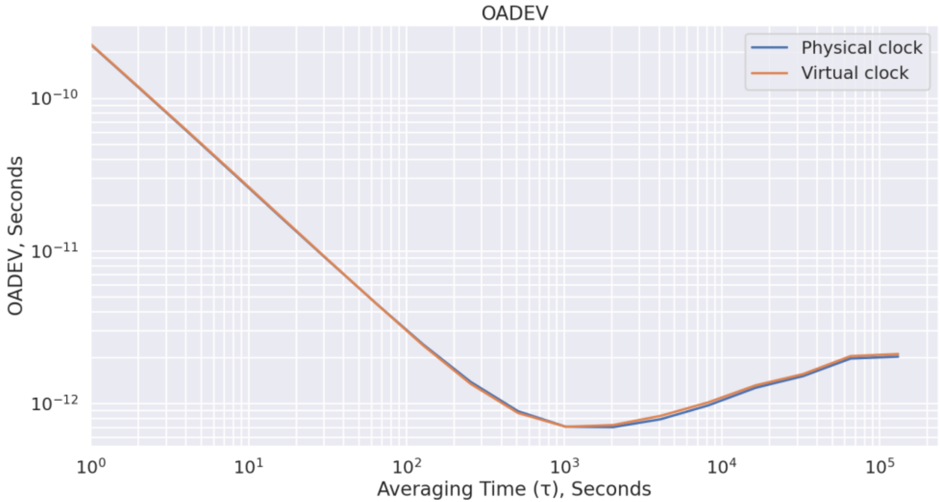

```
{
  "alert_type": "ClockDiscontinuity",
  "clock_id": 6000,
  "node_id": 6,
  "timescale_id": 1,
  "message": "No measurement for clock 6000",
  "timestamp": "2025-09-10 08:39:55"
},
```

Data Collection: Hardware Clock Emulation

- **Real clock data** is used to generate **simulated clock data** from a more stable reference.
- By using a pico-stepper, a **physical clock signal** can be emulated.





Previous Study through Simulation

- A previous study using **generated independent clock datasets** was done.
- Different Ensembling Algorithms.
  - Natural Kalman.
  - Implicit Ensemble Mean.
  - Reduced Kalman.
  - TA.
  - AT2.
  - **Kalman Plus Weights***.
- KPW proved more versatile and a modified version served as the base for the implementation of anomaly mitigation algorithms.
- Different **clock profile** combinations.
- Selecting **weight window size** and estimating the **limits of anomaly detection**.

Verification & Validation Campaigns

	Verification	Validation
Scope	De-risking the whole system using emulated Rubidium clocks	Test the system in a real controlled environment using physical clock signals
Main Objectives	• Detect early problems • Verify the realisation of a physical output	• Ascertain system functionality in a real lab scenario • Determine the limitations of using Caesium clocks
Where?	Safran Timing Laboratory Granada, Spain	ESTEC UTC Laboratory Noordwijk, Netherlands

Verification & Validation Campaigns

Verification Campaign

- **System correctness** (WR, API, connectivity...)
- Node inclusion and exclusion
- Clock inclusion and exclusion
- Anomalies
  - Link failures
  - Phase Jumps
  - Frequency Jumps

Validation Campaign

- System assessment
  - Setup with physical clocks
- Fault tolerance and recovery
  - Clock failures
  - Node failures
  - Emulated Jumps
- **Long run test**

Verification: Equipment

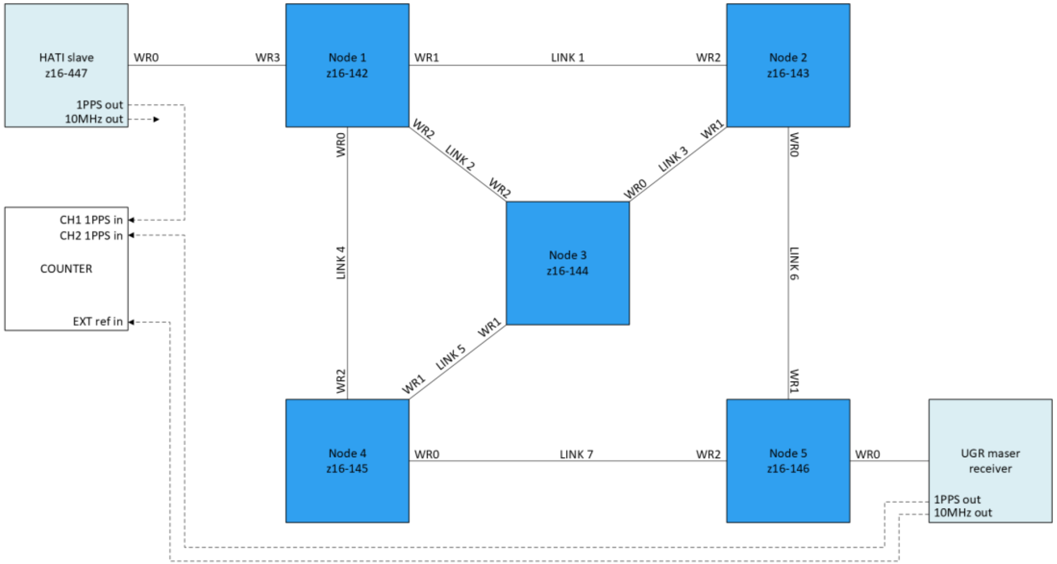
- A study **prior to validation**. Used to ascertain the system capabilities.
- The verification campaign was done in Safran premises with the following equipment:

- **Equipment under test:**
  - 5 x Nodes (WR-Z16 LJ 4.0) which will fit an additional Septentrio mosaic-t GNSS
  - 8x SFP 1310nm (blue).
  - 7x 1490nm (purple).
  - 5x optic fibre 2 meters (links 1 to 5)
  - 2x optic fibre 50km (links 6 and 7)

- **Support testing equipment**
  - Swabian – TimeTagger ultra
  - Agilent 53230A Universal Frequency Counter – MY5000366
  - SecureSync 2400 (Safran)
  - Microsemi – Phase noise test 3120A
  - Oscilloscope
  - External computer to run test platform
  - Additional White Rabbit device used specifically to extract PPS and 10MHz signals from the clock ensemble's WR master output.

Verification: Topology

- Ensemble composed of **5 emulated Rubidium clocks** using a Maser reference. The contribution of said reference is removed.
- Each test is run for **at least 24 hours**.
- Ensemble Network.
  - 5 nodes.
  - Each node with a simulated Rubidium.
- Distribution Network.
  - 1 node. Its output is measured against the reference.



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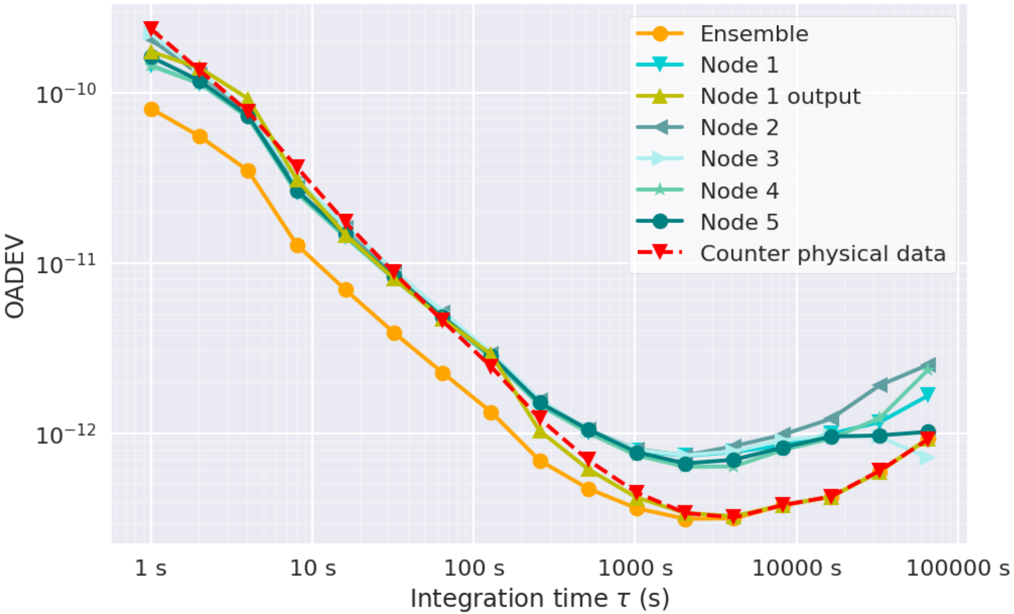
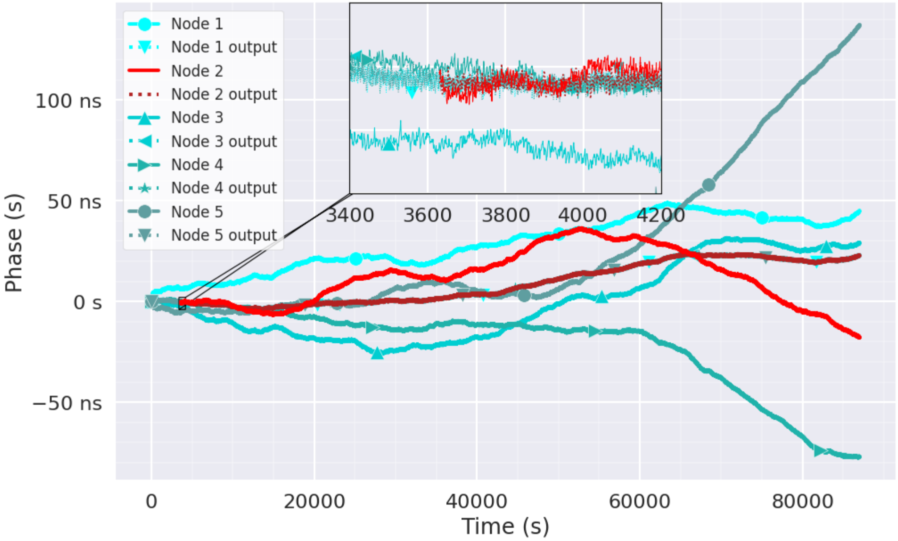
Verification: Baseline and Physical output

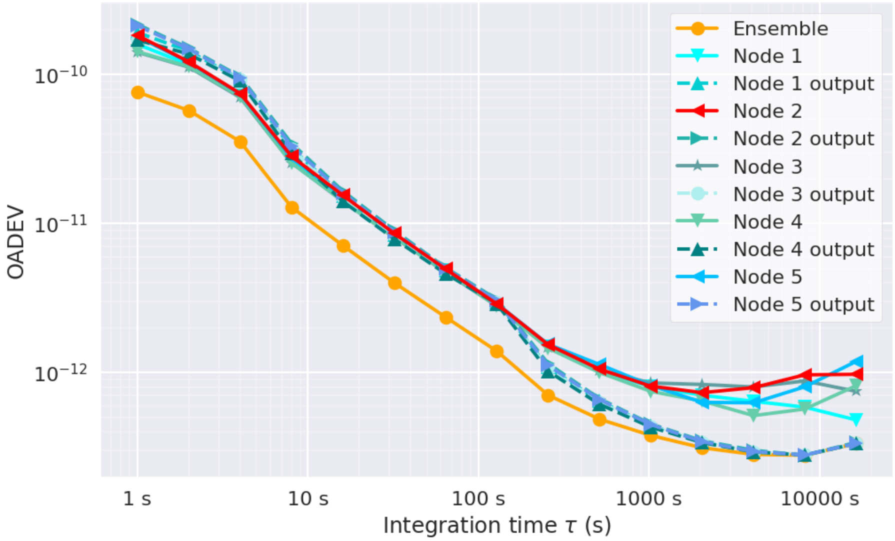
- Baseline without anomalies.
- Run for almost **3 days**.
- The **ensemble** is **more stable** than any of the rubidium clocks.
- Both the **node internal ensemble clock** and the **physical clock** converge to the ensemble.



Verification: Clock Inclusion

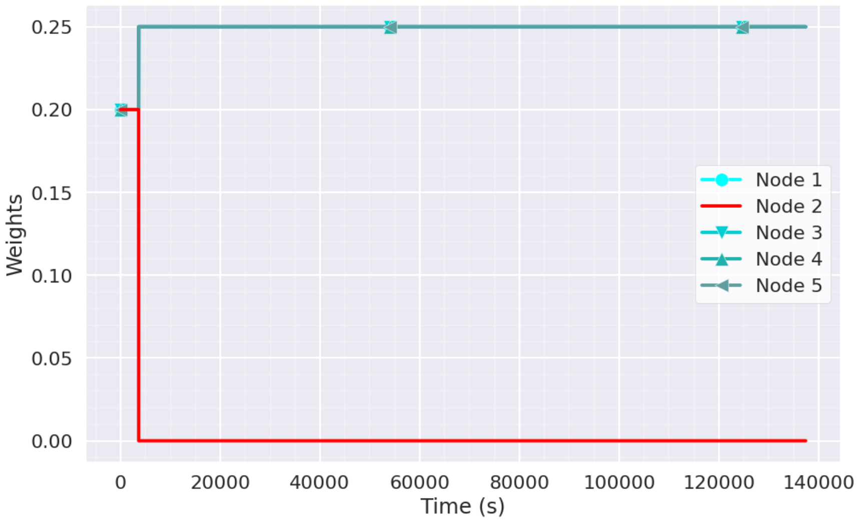
- A clock is included after an hour of normal running.
- The system stability is not compromised.

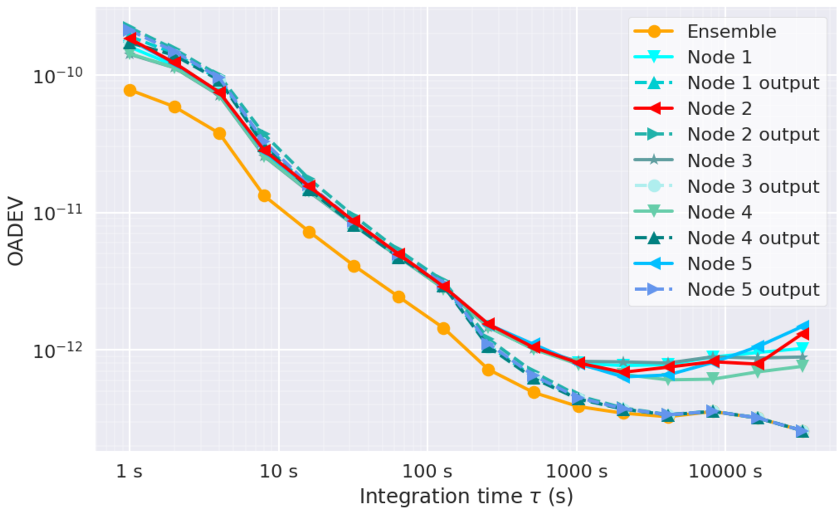




Verification: Manual Clock Exclusion

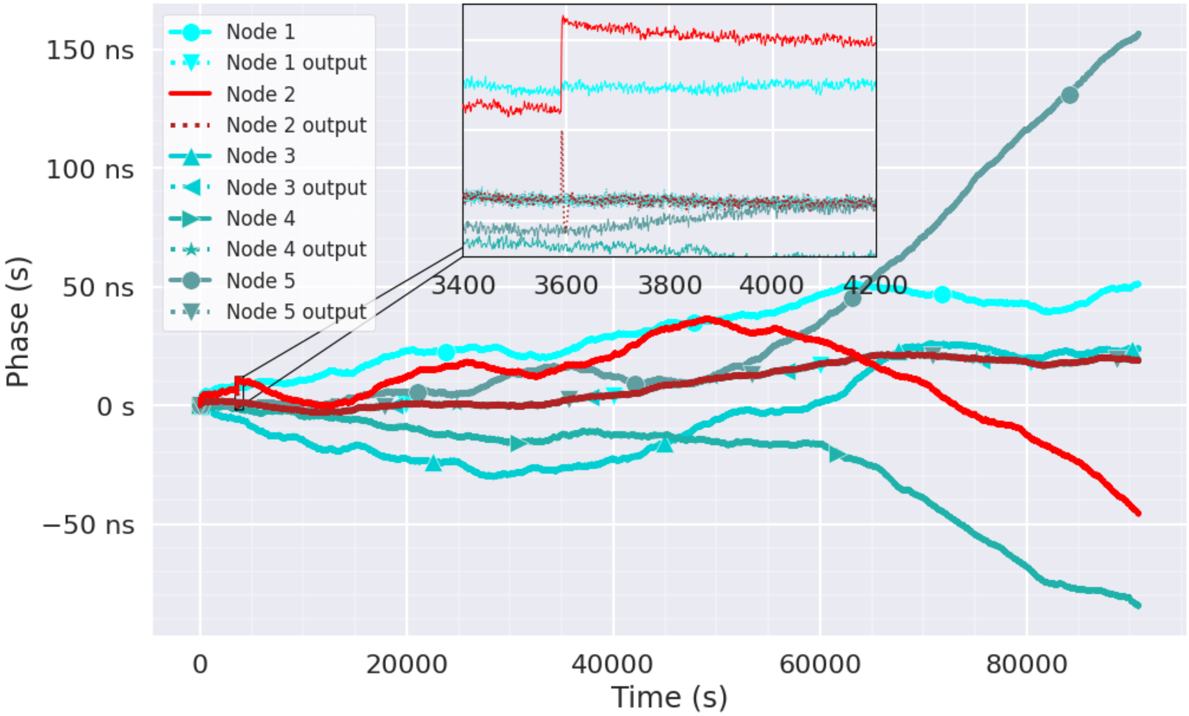
- A request through the **REST API** is sent to remove the **contribution** of a clock.
- The **weight** of the excluded clock is set to **zero**.





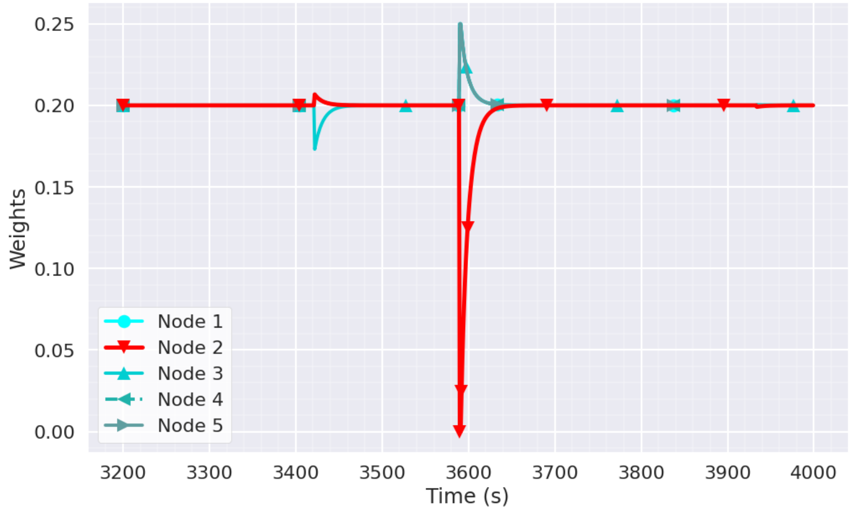
Verification: Phase Jump

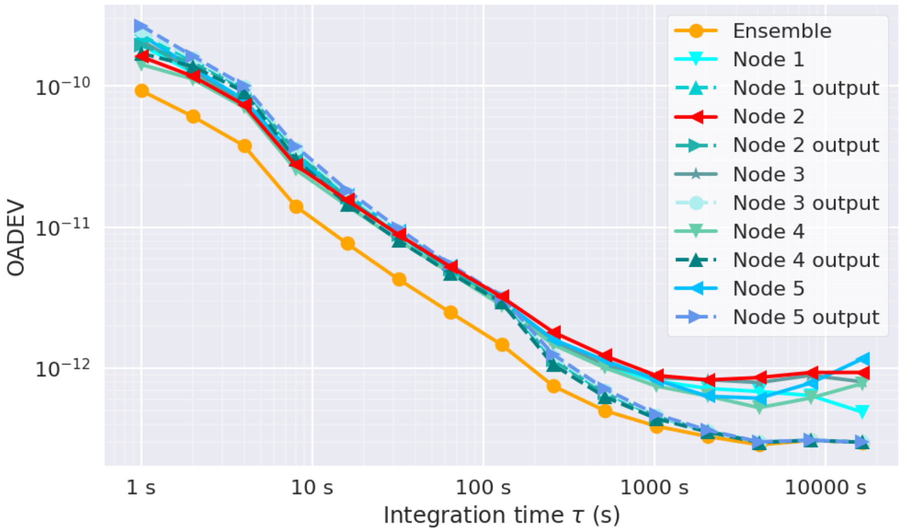
- Jump of size 5e-09s ~1 hour after initialization.



Verification: Phase Jump

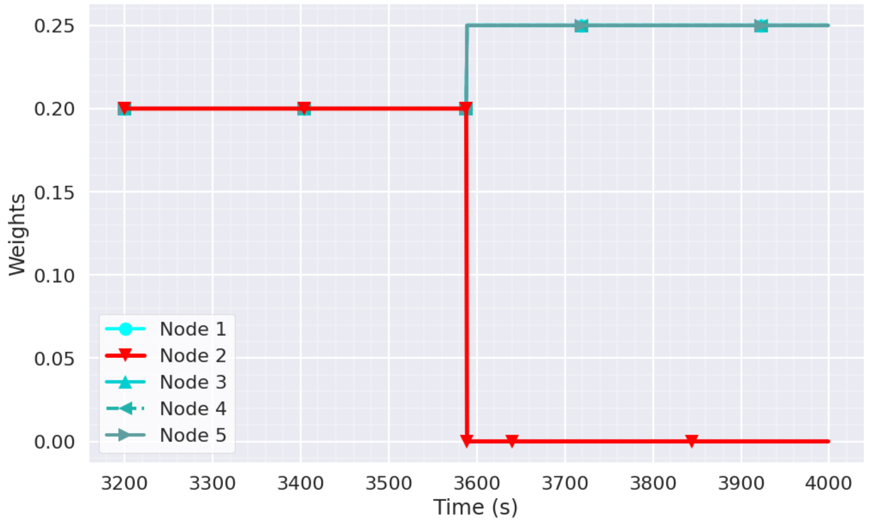
- The system detects the jump and sets the clock weight to zero until recovered.

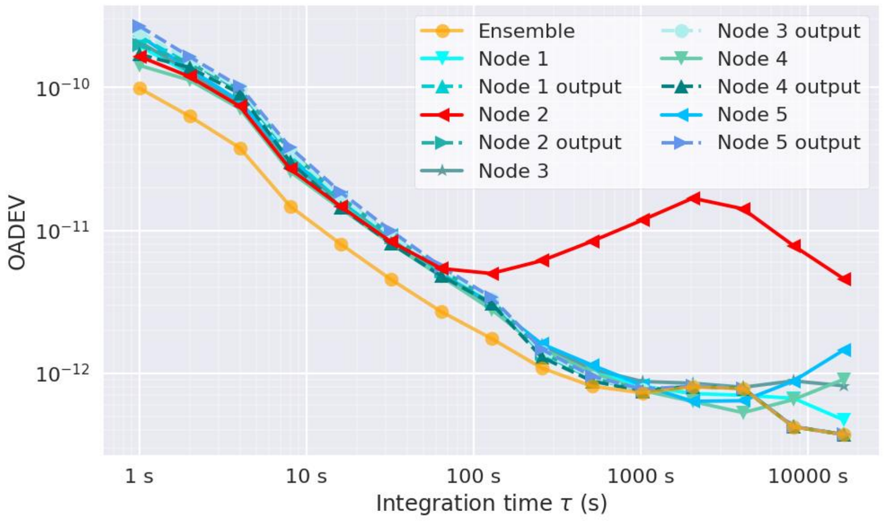




Verification: Simulated Frequency Jump

- Jump of size 2e-10 ~1 hour after initialization.



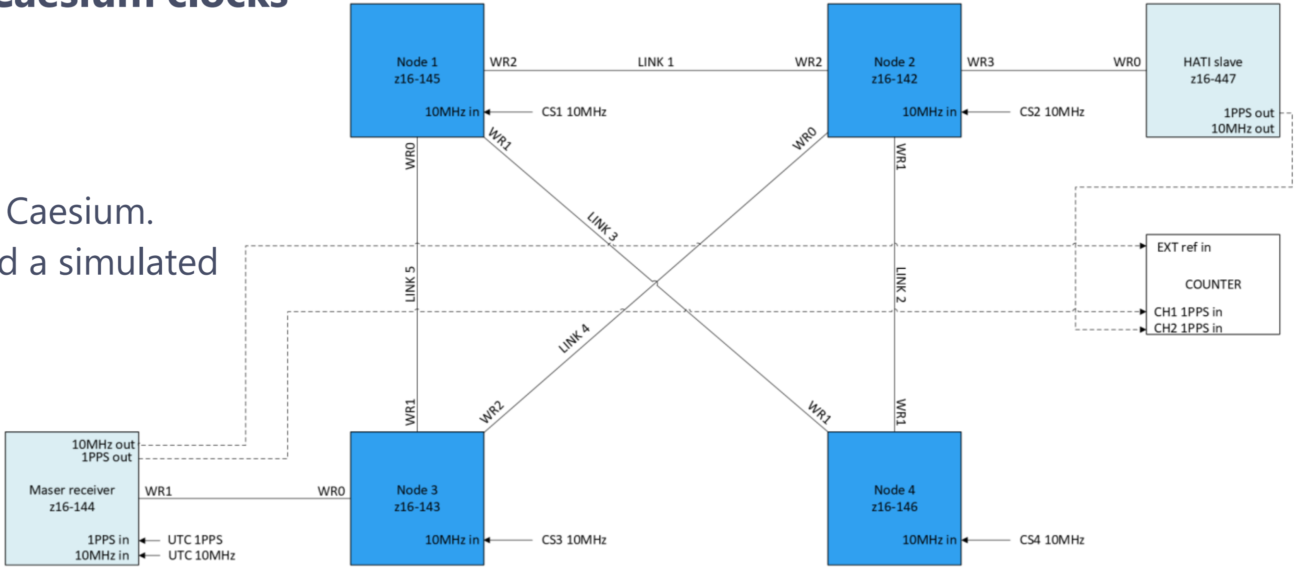


Validation: Equipment

- Tests run at **ESA ESTEC facilities,** ensuring that testing is performed in a controlled and consistent environment.
- **Available Laboratory Setup:**
  - 1x Rubidium clock 10 MHz SMA
  - 4x Caesium clock 10MHz SMA
  - 3x Maser clock 10MHz SMA
  - 4x SMA to GNSS antenna
  - 1x Oscilloscope to check 10MHz output.
  - 1x FemtoStepper (Safran)
- Provided by Safran:
  - 6x WR-Z16 with Coherent Clock capabilities.
  - Fiber and SFP.
  - Swabian TimeTagger Ultra

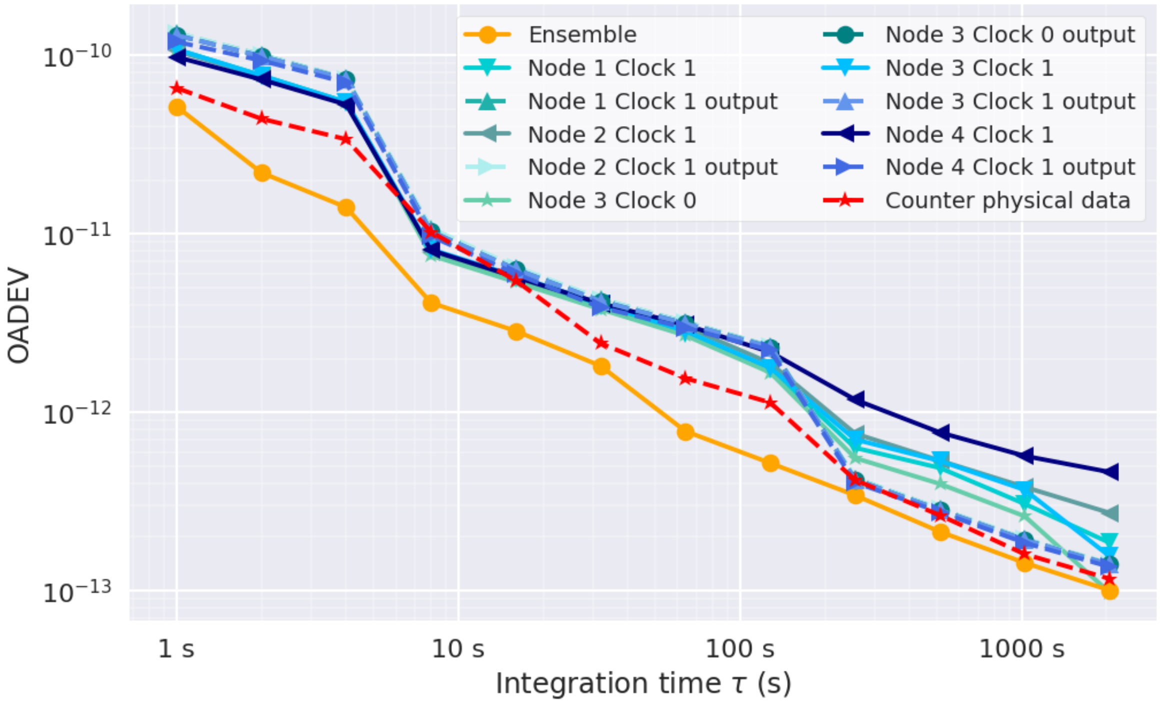
Validation: Topology

- Each test is run for at least **2 hours**.
- Ensemble of **4 physical Caesium clocks and an emulated one**.
- Ensemble Network.
  - 4 nodes.
  - Each node with a physical Caesium.
  - Node 3 with a physical and a simulated Caesium.
- Distribution Network.
  - 1 node.
  - 1 counter.



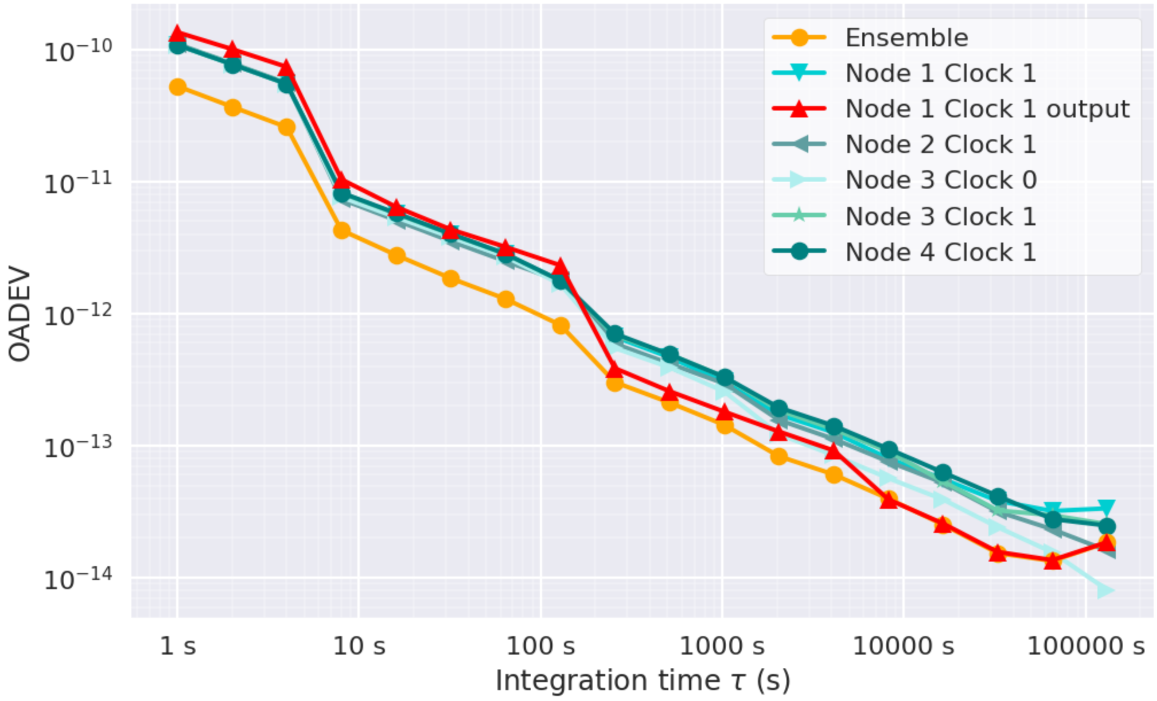
Validation: Baseline

- Initial test without anomalies left running for **two hours**.
- The **output** converges slower to the **ensemble.**
  - The steering algorithm is not fine enough.
- The **physical output** converges.



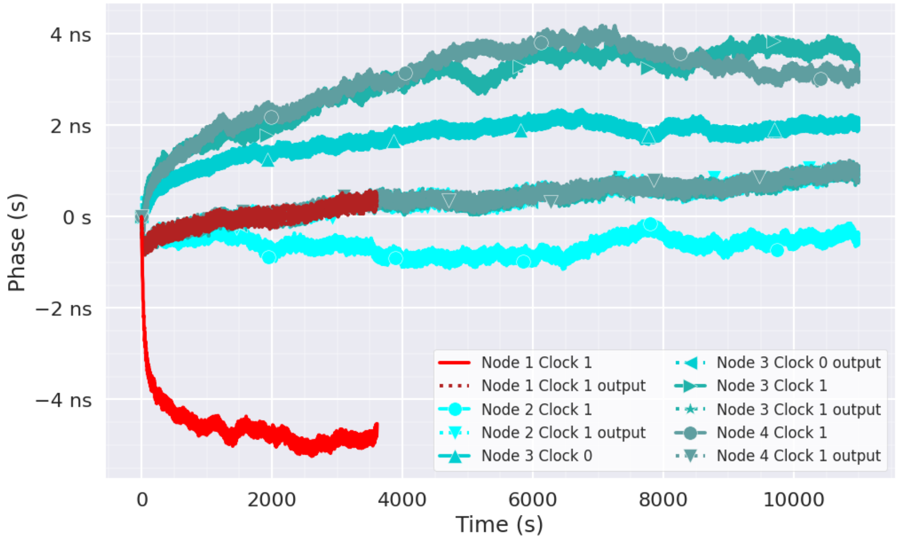
Validation: 10 days run

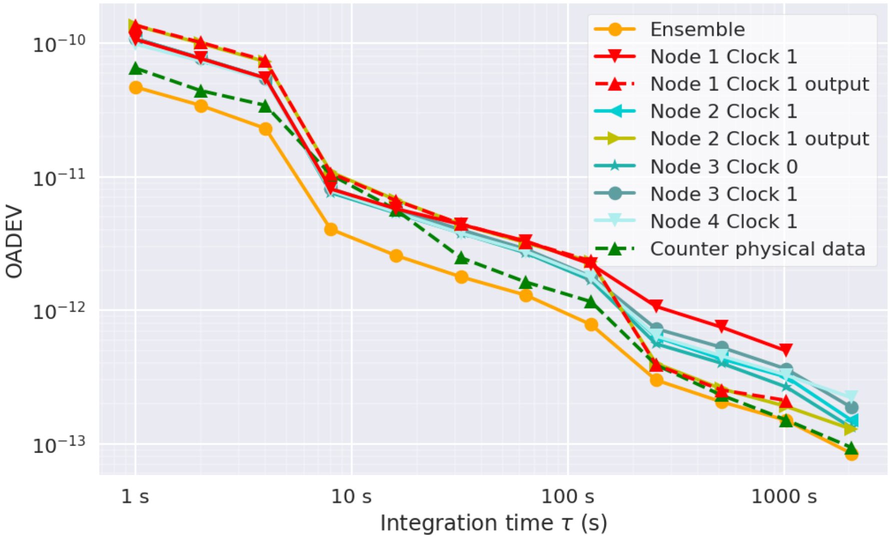
- The clock ensemble run for **10 days** without issues.



Validation: Node Failure

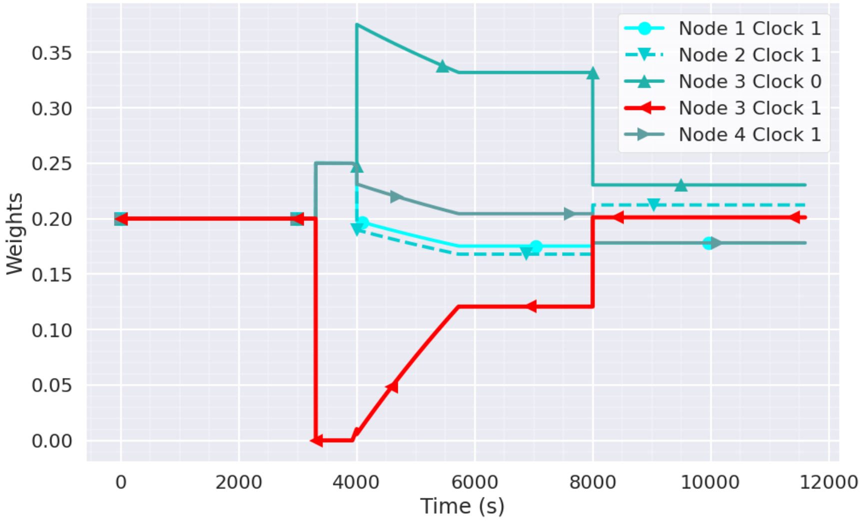
- Emulated failure of node 1. It was **powered off**.
- It can be appreciated that there is less data from that node.

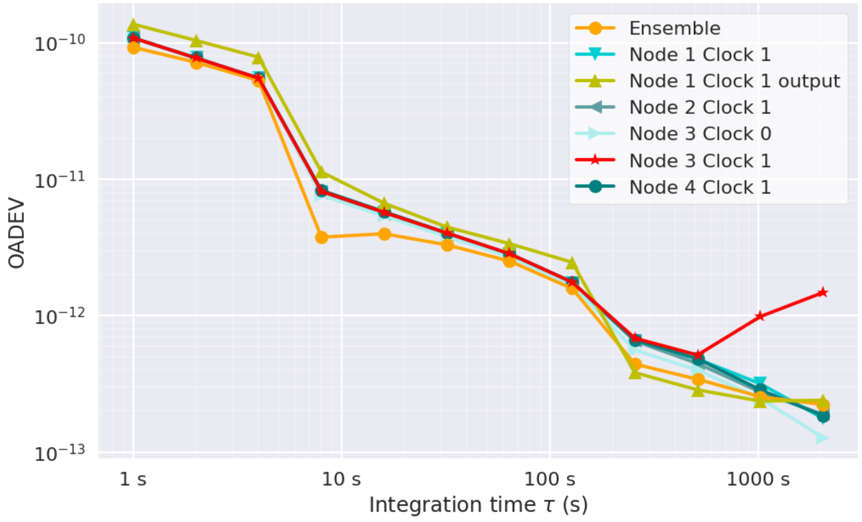




Validation: Clock Failure

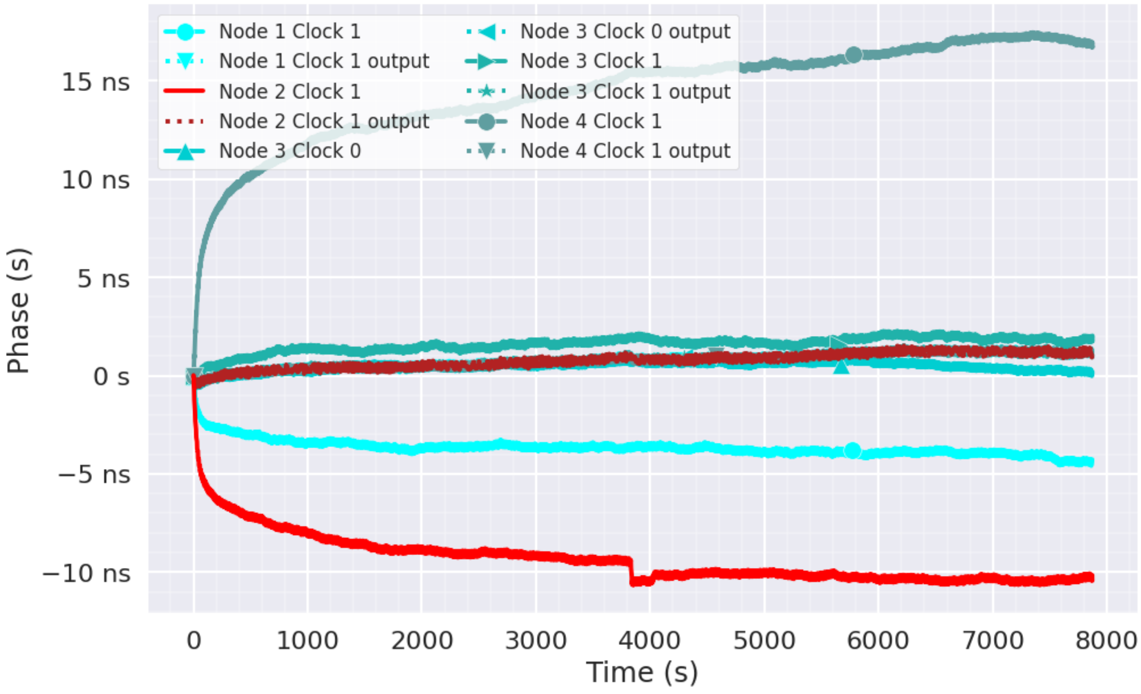
- 10 minutes physical clock failure, the physical connector of **Caesium3** (on node 3) was **removed** and **reinserted** after 10 minutes.





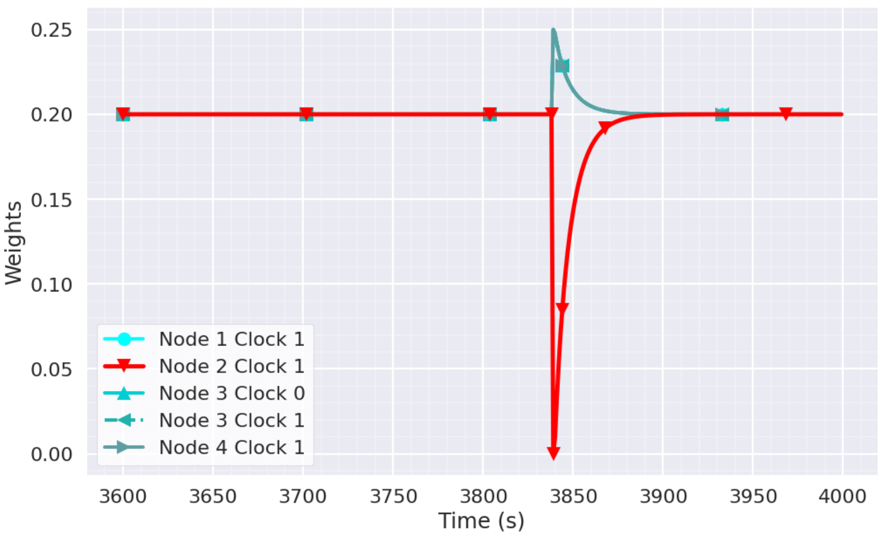
Validation: Emulated Phase Jump

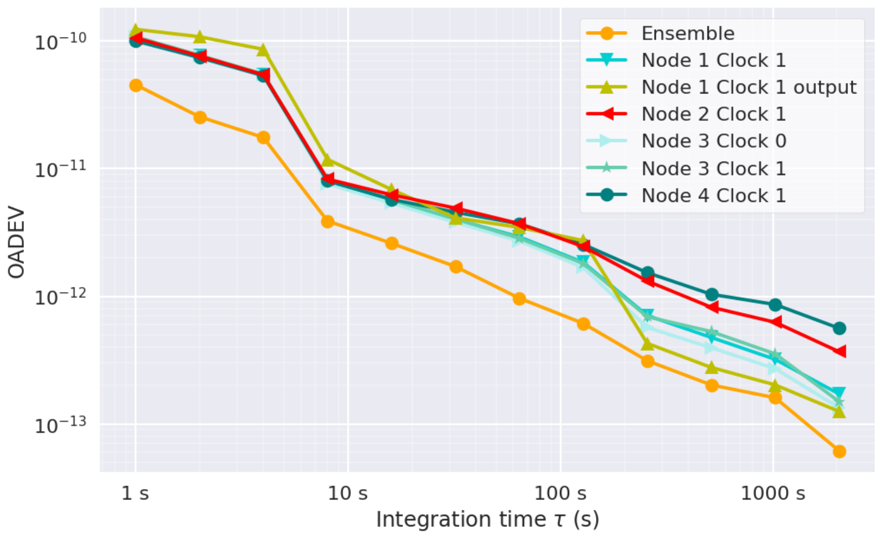
- **Emulated phase jump** of 1ns on physical Caesium 2 using a **FemtoStepper**.



Validation: Emulated Phase Jump

- The jump is small enough to not greatly affect the stability, yet it can be detected.





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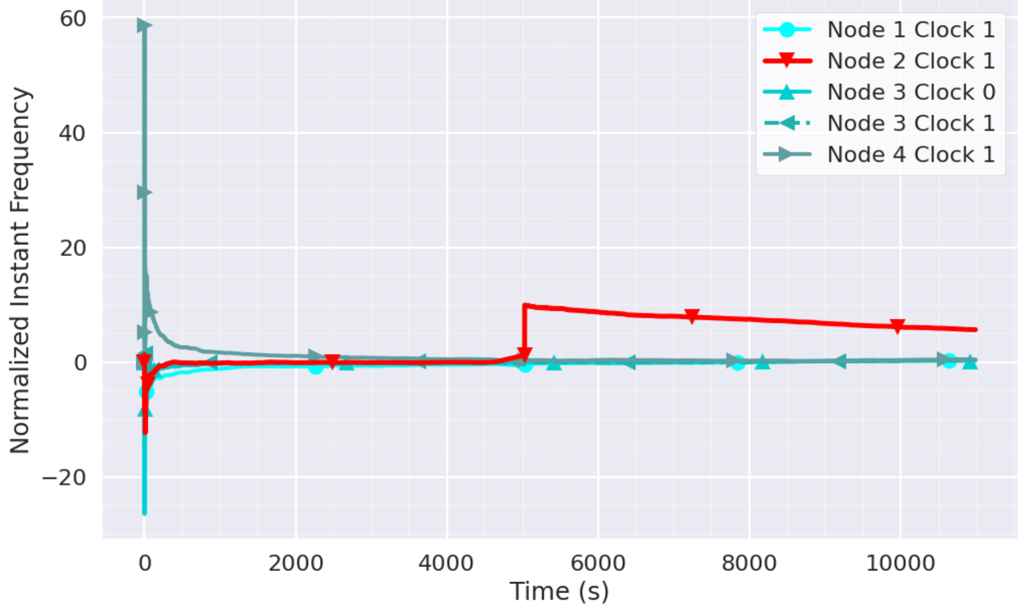
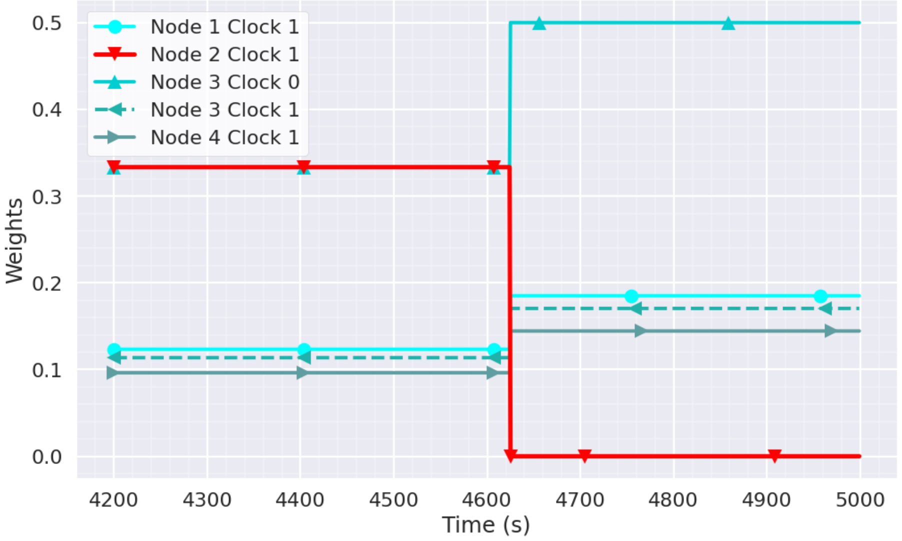
Validation: Emulated Frequency Jump

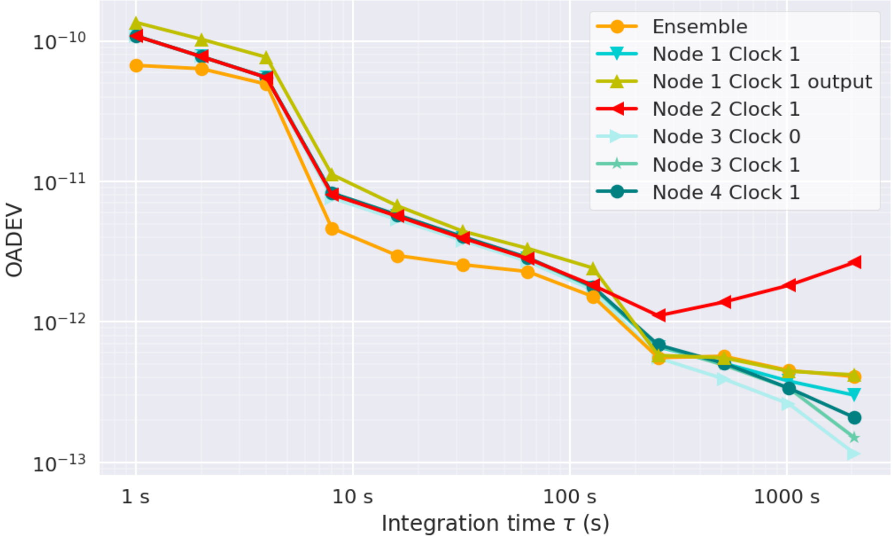
- **Emulated frequency jump** of 1e-11 on physical Caesium 2 using a **FemtoStepper**.
- The minimum detectable jump value is lower with Caesiums than with Rubidiums.
- It can be observed in the estimated frequency from the **internal Kalman State**.



Validation: Emulated Frequency Jump

- It has a greater effect than the phase jump.





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Chapter 04

Conclusions

Outcomes & Recommendations

- **Key Project Outcomes**
  - For **Rubidium clocks**, our system provided an enhancement in both **robustness** and **stability**.
  - For **Caesium clocks**, the enhancement in **stability** occurred at **long integration times**, however the **robustness is improved**, nonetheless.

- **Technical improvements and recommendations for future activities:**
  - Execute the **pending UTC test** to ensure the accuracy between all nodes (relative) versus UTC (absolute).
  - Integrate **GNSS-based clocks** within the ensemble.
  - Introduce **steering** improvement such as steering algorithms.
  - Support **multiple reference clocks** in the ensemble.
  - Perform necessary **firmware changes** to achieve 10MHz jitter/phase noise while switching clock reference for output.
  - Support for high performance alternative.

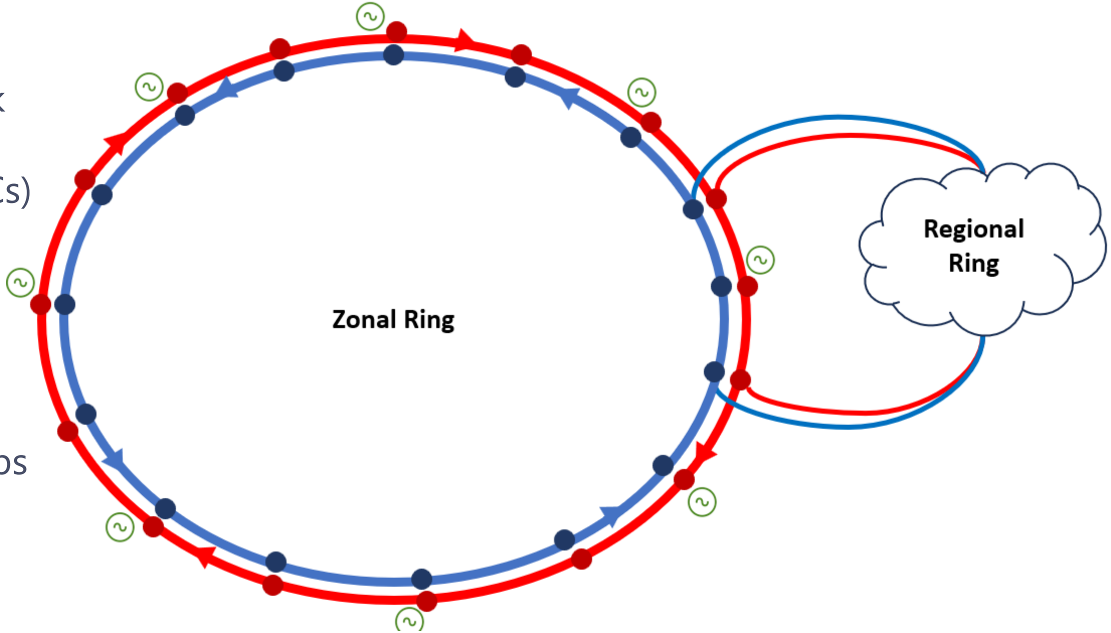
Technical Roadmap to Telecom Market

- **Ensure a smooth transition from TRL 5 to full commercial readiness. The progression includes:**
  - Completion of remaining technical activities
  - Execution of multi-site pilots
  - Achievement of TRL 7 and final product hardening before scale-up

Phase	Objective	Key Activities	Output	Timeline
A	TRL 6	UTC testing, GNSS ensemble integration, improved steering, jitter reduction	Enhanced prototype	0–12 months
B	Operational Pilots	3–5 pilots with GCIs	Pilot reports & case studies	12–20 months
C	TRL 7	SLA validation in real networks	Commercial ready version	18–24 months
D	Scale up	Hardening, deployment tooling, 24/7 monitoring	Full product catalogue	24–36 months

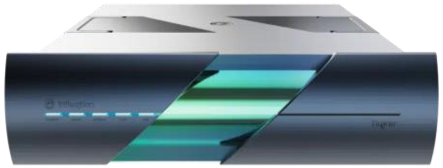
Technical Roadmap to Telecom Market

- **cnPRTC**
  - Fulfil ITU-T G.8272.2
  - Add specific interface for UTC(k)
  - Add GNSS (PRTC class B) into the clock ensemble
  - Optimized steering for ePRTC clocks (Cs)
  - Focus on red & blue redundancy
- **Zonal Ring (PoC)**
  - Maintain cost-effective (full FPGA)
  - Support of dual rings (red & blue)
  - Support of rubidium on alternative hops
  - Add GNSS (PRTC classB) at multiple location



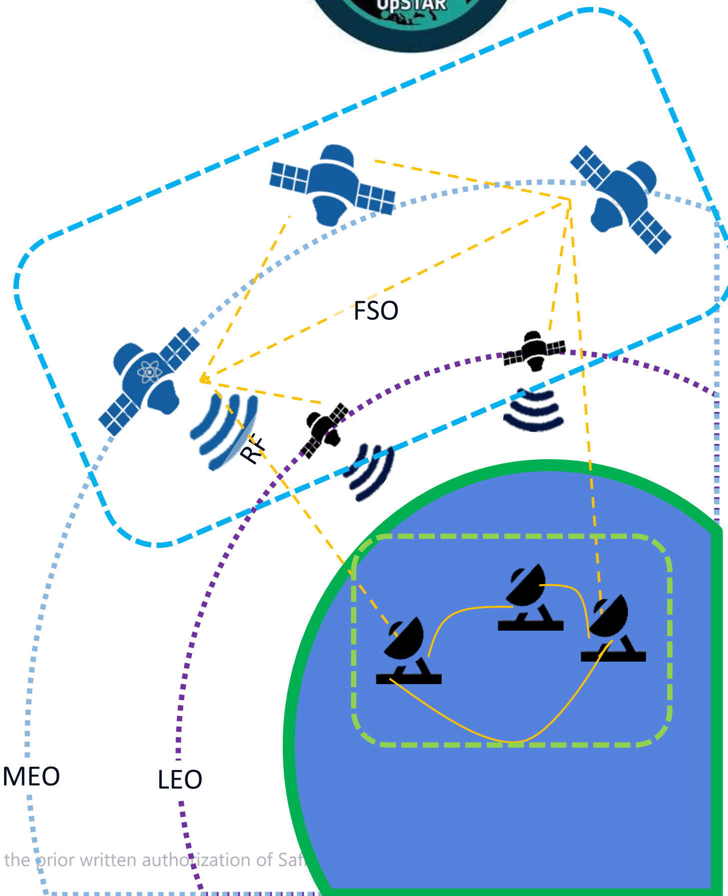
High Performance Alternative

- **Targeting NMI, Defense Timescales, Space ground segment**
- **Compatibility of distributed clock ensemble with external:**
  - High performance Phase comparator
  - High Resolution Offset Generator (HROG) / Femtostepper
  - Optimizated for:
    - Safran Ground Active Hydrogen Maser
    - Infleqtion Tiqker Optical Clocks
  - Other frequency distribution techniques
- **Improved features**
  - Fully redudant chain (Red & Blue)
  - WR distribution with jitter < 200fs RMS
  - Integration with Safran TaaS



Space Ground and Flight Segments Ensembles

- **Accurate time transfer**
  - **Free Space Optic Inter-Satellite Link & Ground-to-Satelite**
  - RF for LEO or smallsat
  - Fiber for ground segment
- **Resilient Meshed Topology**
  - No defined grandmaster:
  - Adding/Removing node seamless
    - Link might change each 60s
- **Combined multi-class of clock**
  - MEO: Some High-end included (Passive Hydrogen Maser)
  - LEO: Focused on mid-end clocks (Rubidium)



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