spectratime
an Orolia brand

ATOMIC CLOCKS TECHNOLOGIES FOR GALILEO
&
RELATED APPLICATIONS

Pascal Rochat
Managing Director, Founder

rochat@spectratime.com

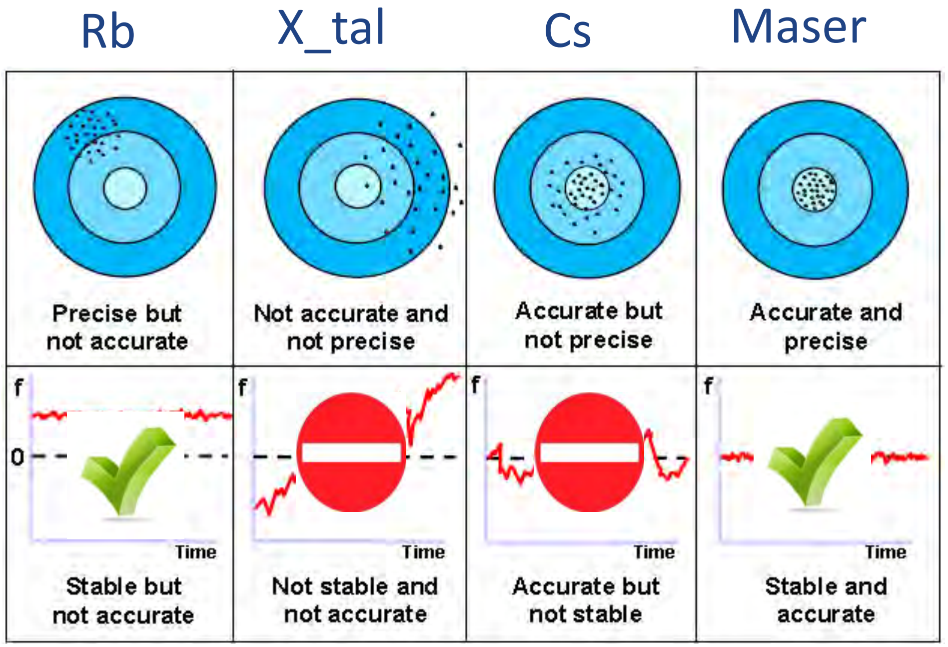
orolia

GNSS ONBOARD ATOMIC CLOCKS REQUIREMENTS DEPENDS ON :

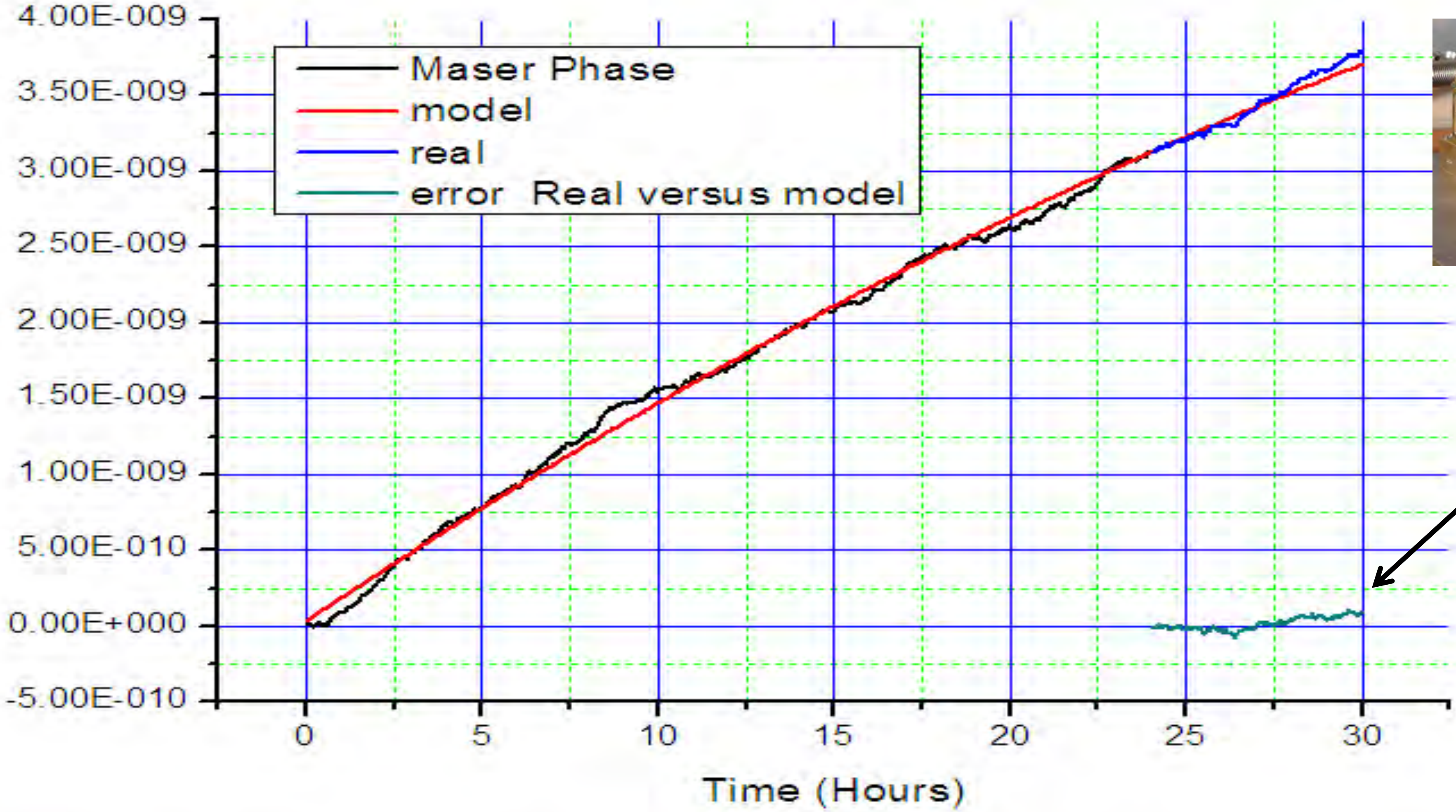
- Autonomy (clock model upload rate: tens of minutes to days)
- Navigation and positioning accuracy (meters to tens of meters)
- Satellite platform design and technical requirements
- Availability of the reference signal on board within specifications

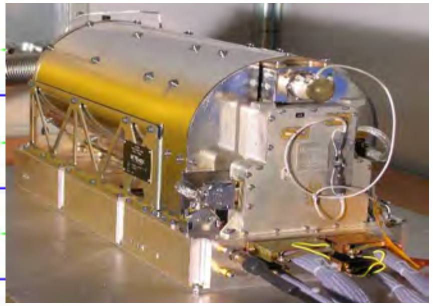
Clocks key parameters :

- Long term drift or drift stability
- Short term stability
- Frequency sensitivity to environment (temperature, magnetic field, voltage, radiations)
- Reliability figure of onboard elements versus requested Availability figure



POSITION ERROR INDUCED BY THE ONBOARD PASSIVE MASER





~ 0.1 ns

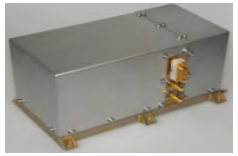
→

~ 3 cm

SPACE RUBIDIUM (RAFS) AND PASSIVE HYDROGEN MASER (PHM)

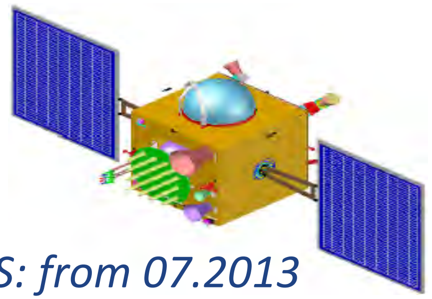
Spectratime delivered more than 100 RAFS flight models and 50+ PHM flight physics packages.

3.2kg

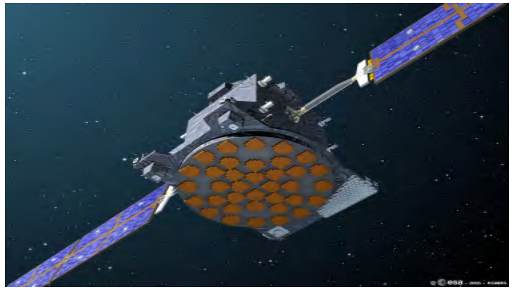


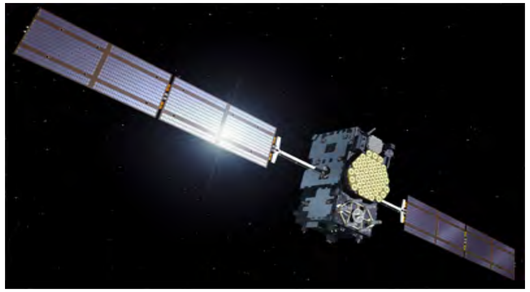
18kg

Both clock technologies have a number of years of flight experience, of which more than 100 RAFS, and 45 PHM are actually flying in various orbits.

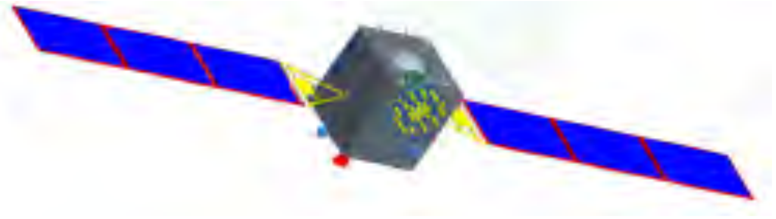


IRNSS: from 07.2013





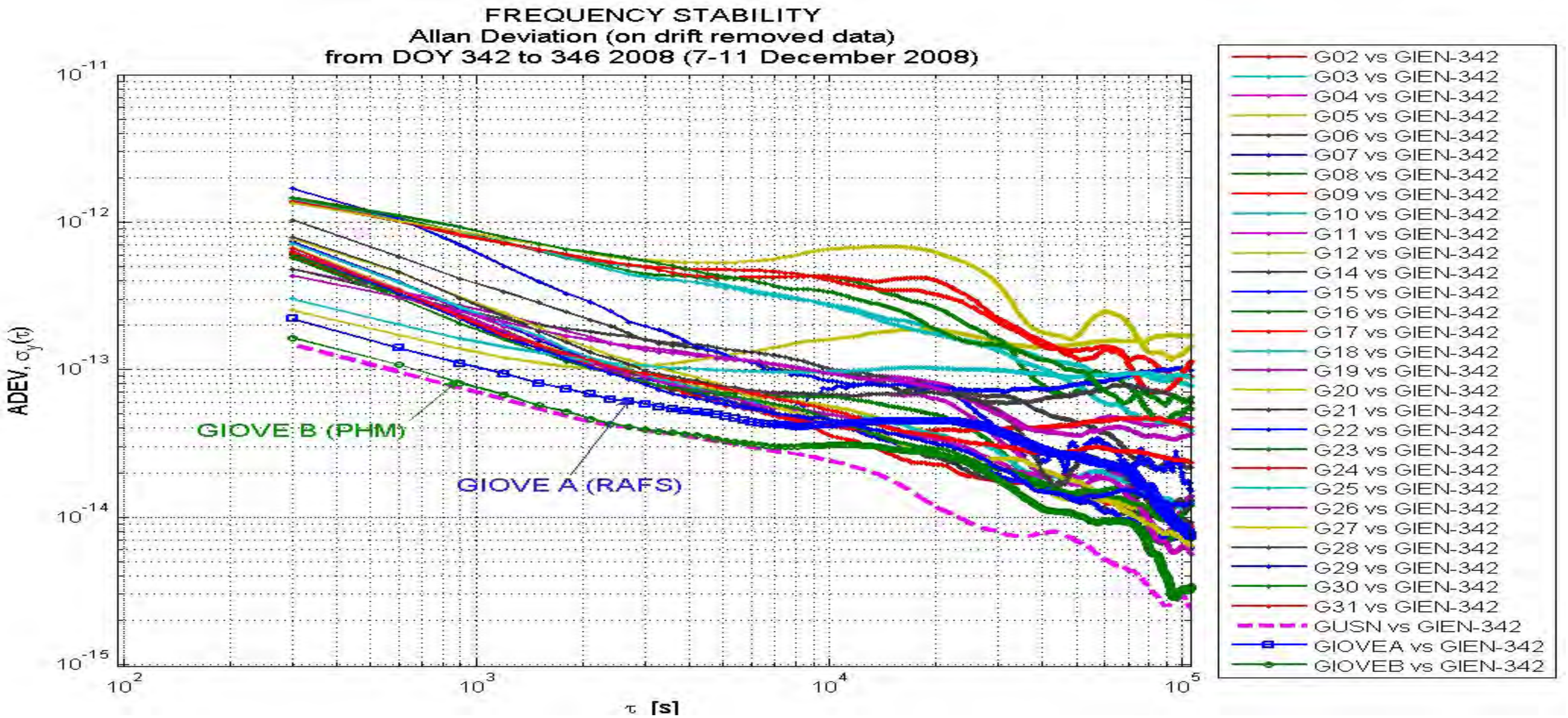
Galileo GIOVE –IOV : from 12.2005



BeiDou: from 04.2009

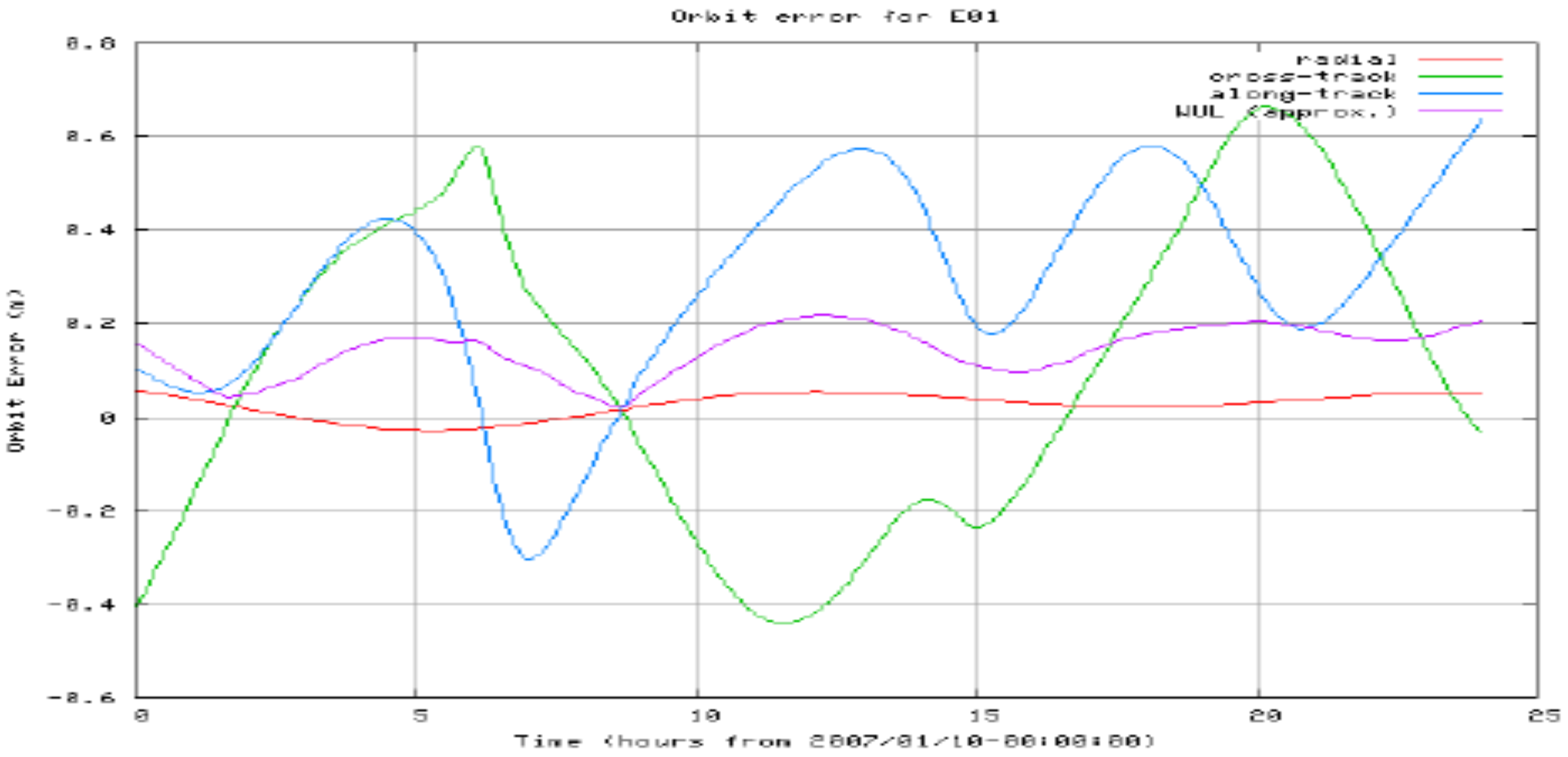
Galileo FOC: 12.2013

FREQUENCY STABILITY COMPARISION BETWEEN GALILEO AND GPS



Source: ESA/GMV , EFTF 2009

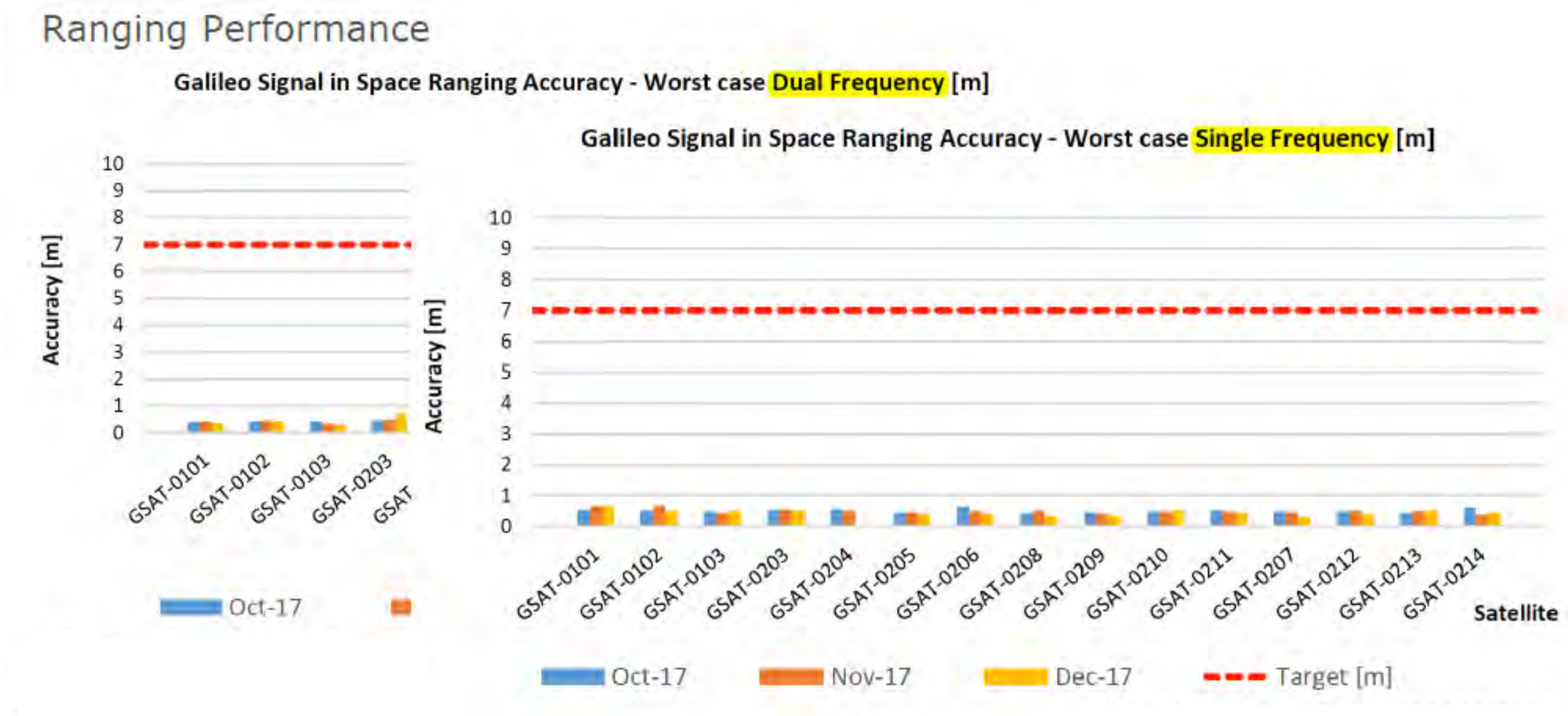
ORBIT PREDICTION ERROR LIMITING THE ON BOARD CLOCK CLOCK MODELLING



GIOVE orbit prediction error

Source: ESA/GMV , EFTF 2009

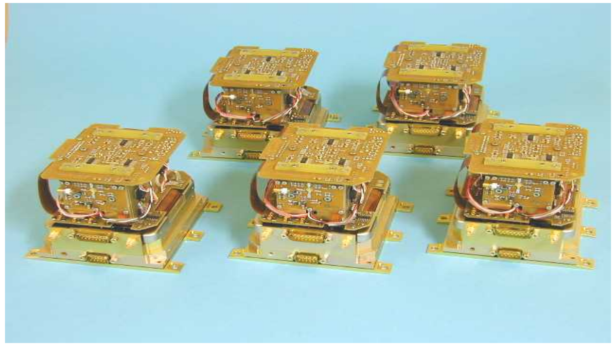
GALILEO SYSTEM PERFORMANCES



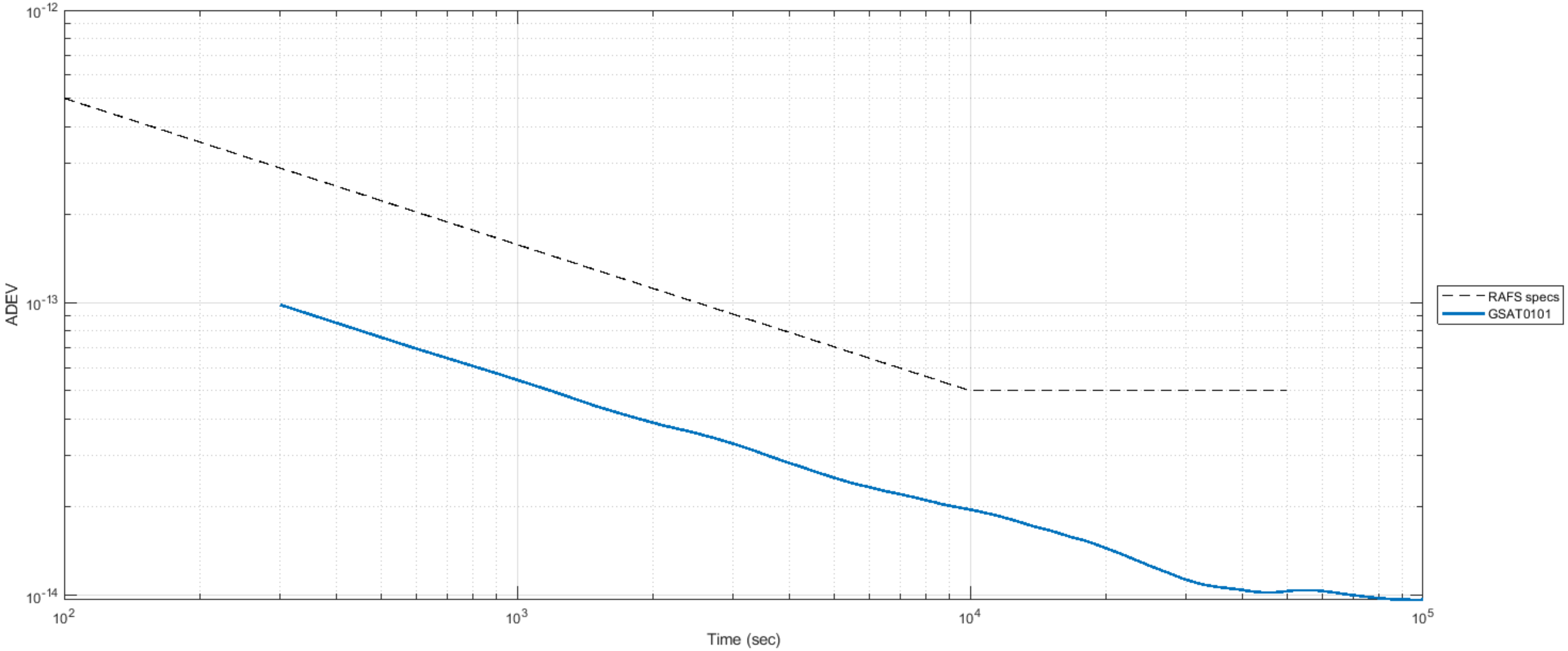
Source: ESA , EFTF 2018

SPACE RAFS DEVELOPEMENT : A 25+ YEARS STORY

- **1991** Space clock first design start for RadioAstron mission
- **1996** First ESA contract for NavSat clock design
- **2002** Life time program of 5 EQM models + QM, meeting all expectations in terms of lifetime (>12 years) along with radiations testing.
- **2005-2006** First launch & Design of 100% Swiss unit
- **2012-2017** Performances improvements under ESA GNSS evolution program



FREQUENCY STABILITY OF ON BOARD RAFS GAST101



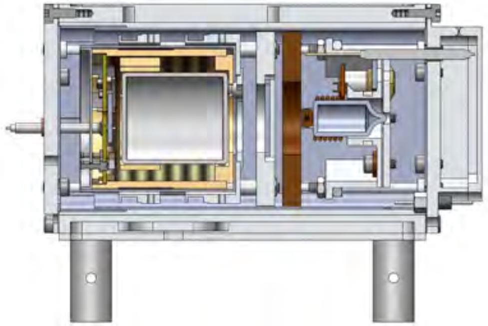
Source: ESA , EFTF 2018

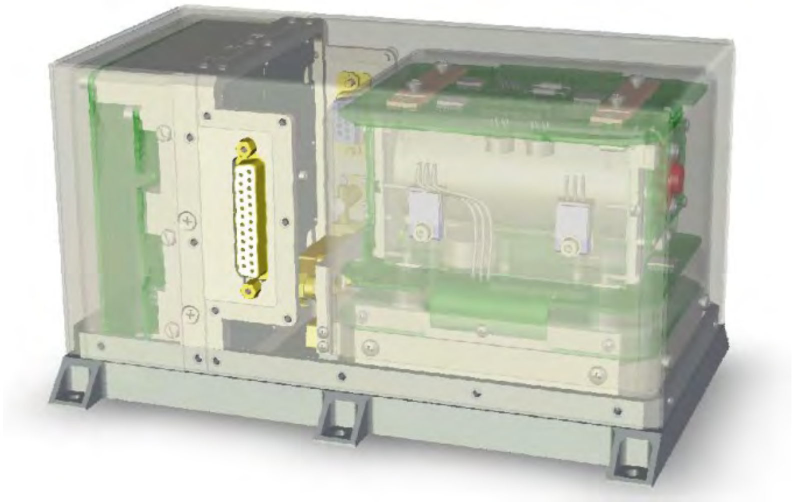
spectratime
an Orolia brand

orolia

PHYSICS PARAMETERS IMPROVEMENT

- The new RAFS design is focused to improve its robustness to external or internal perturbations/variations.
- The RAFS robustness is better as the various key parameters are improved.
- The key parameters are typically:
  - Light shift
  - Pressure shift & Power shift
  - Thermal sensitivity of the cell
  - Thermal sensitivity of the lamp

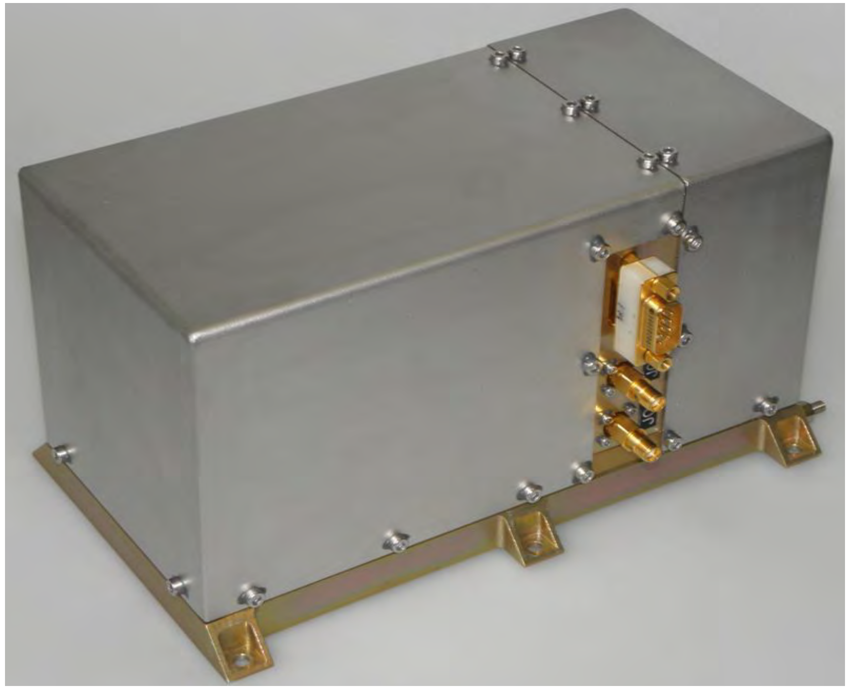


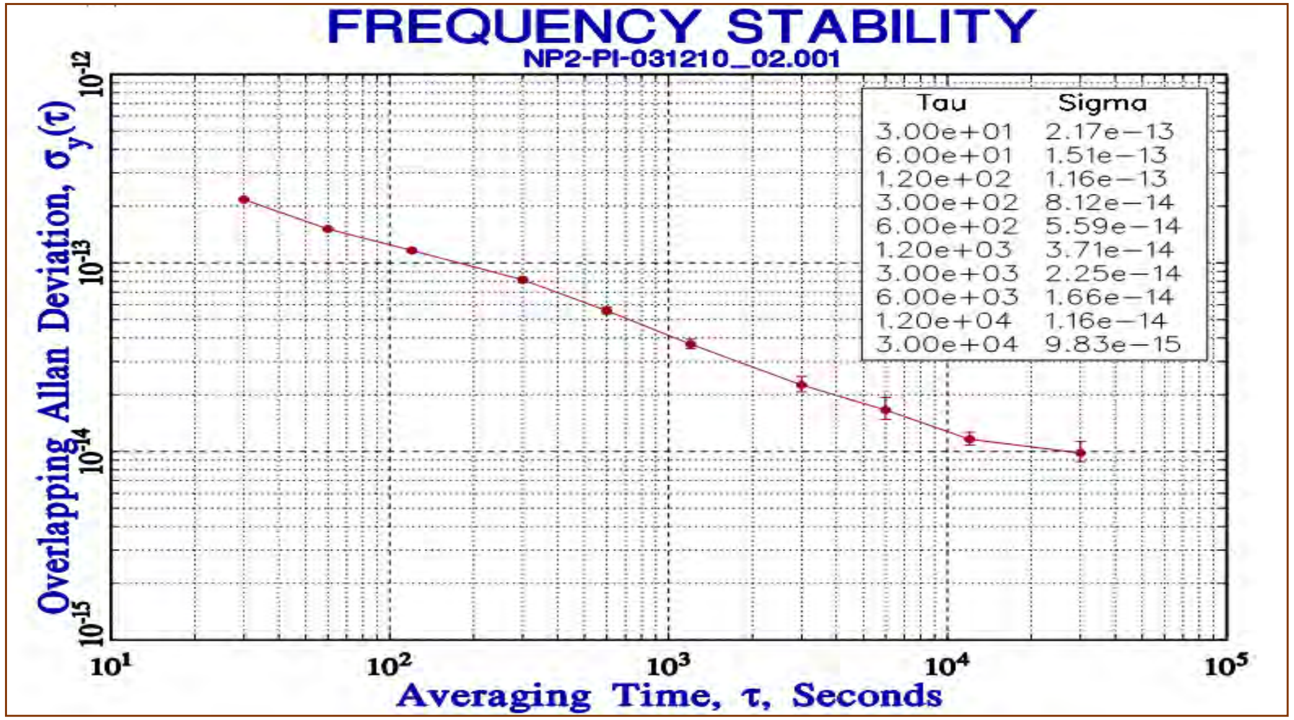


	Old design	New design	Improvement factor
Cell	Gas Mixture 1	Gas Mixture 4	
Lamp	Type A	Type C	
Light shift [/%]	7.0E-11	5.0E-12	14
Pressure shift [/°C/mbar]	3.3E-11	2.0E-12	16
Coef. cell [/°C]	5.0E-12	5.0E-12	Equal
Coef. lamp [/°C]	5.0E-12	-2.0E-11	But not too critical
Short term stab @ 1sec .	3.0E-12	3.0E-12	Equal

SUMMARY

- Because of its excellent reliability, good performances versus quality and price, the rubidium clock is the first choice for the GNSS satellites atomic clocks.
- With the increased batches numbers, the performances has been gradually improved, leading to 2E-14/°C typical temp. coefficient.
- Guaranteed full performances with +-1 °C variations on base plate.





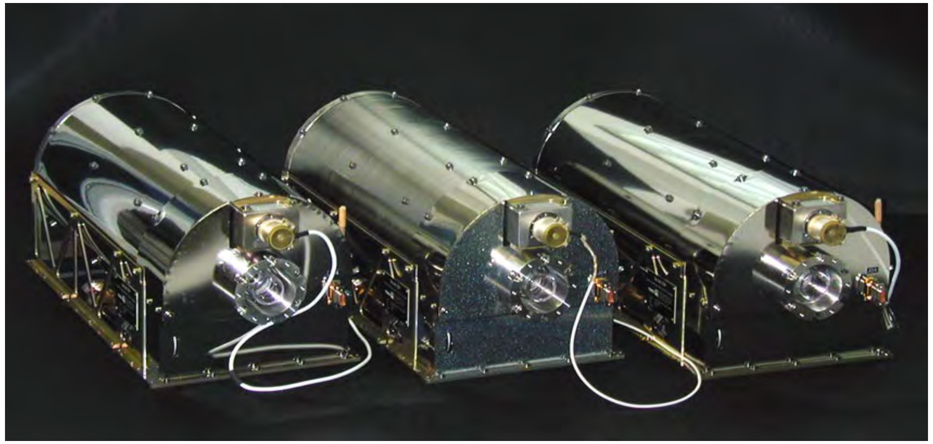
PASSIVE MASER DEVELOPEMENT HISTORY

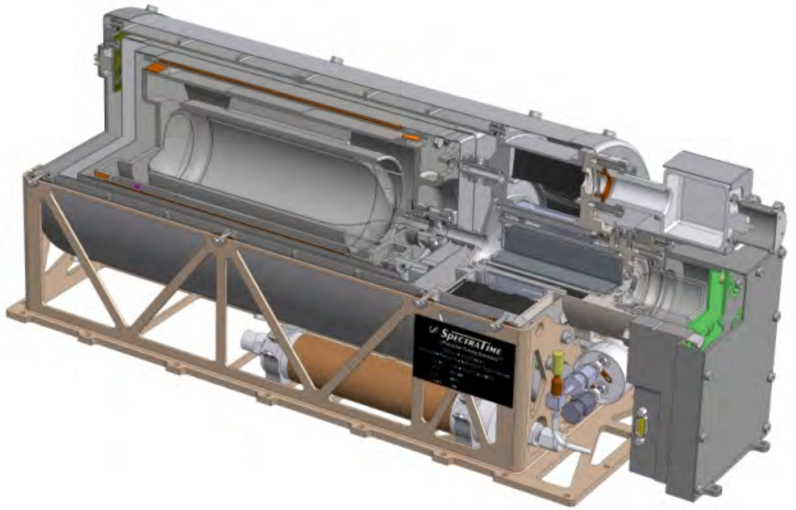
- **2000** Set-up of consortium constituted of the Observatory of Neuchatel , Selex Galileo & Spectratime and start of SPHM development program
- **2003** Industrialisation program & lifetime verification program
- **From 2009** Set-up of production & tests capability up to 2 SPHM / month.
- **2010** Achievement of full stability on ‘Mini Maser’, physics package only 8Kg
- **2012-2018** Qualifications program of mini Maser & electronics package improvements

Observatoire de Neuchâtel

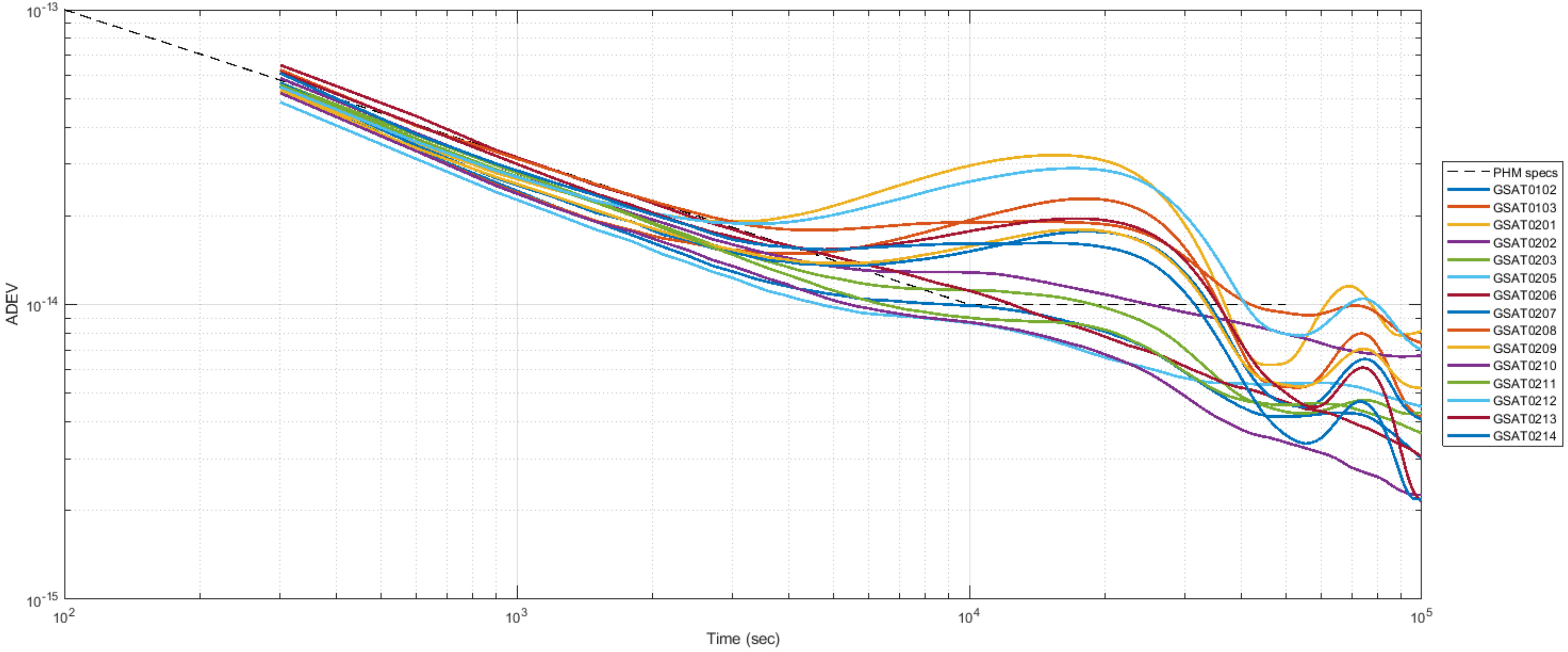
SELEX GALILEO

spectratime an Orolia brand





FREQUENCY STABILITY ON GALILEO SATS PHM



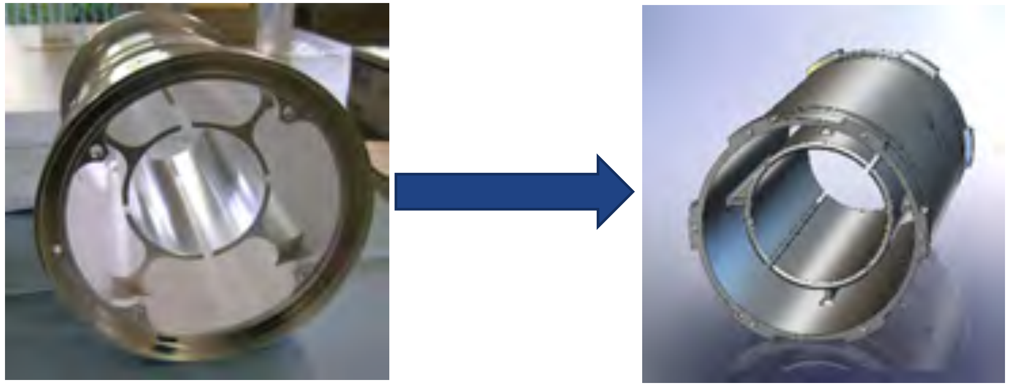
PASSIVE MASER PHYSICS PACKAGE SIZE/WEIGHT REDUCTION

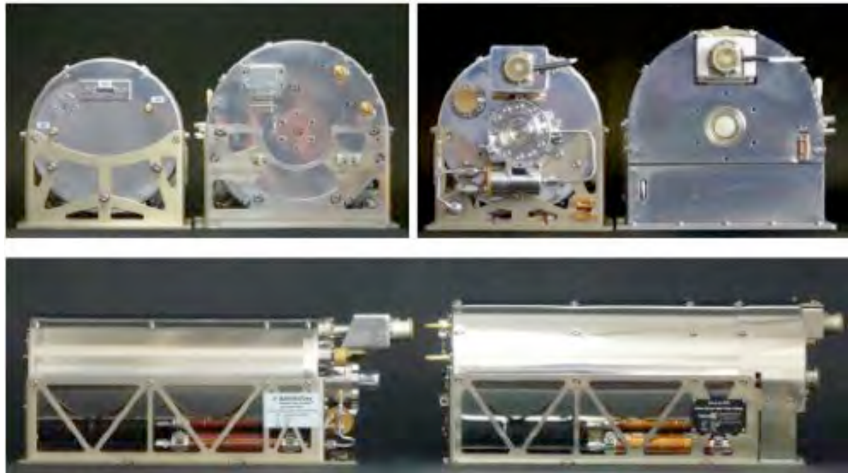
Key improvements :

- Microwave Cavity size reduction
  while keeping same **quality factor Qk**
- Keeping same H storage bulb volume

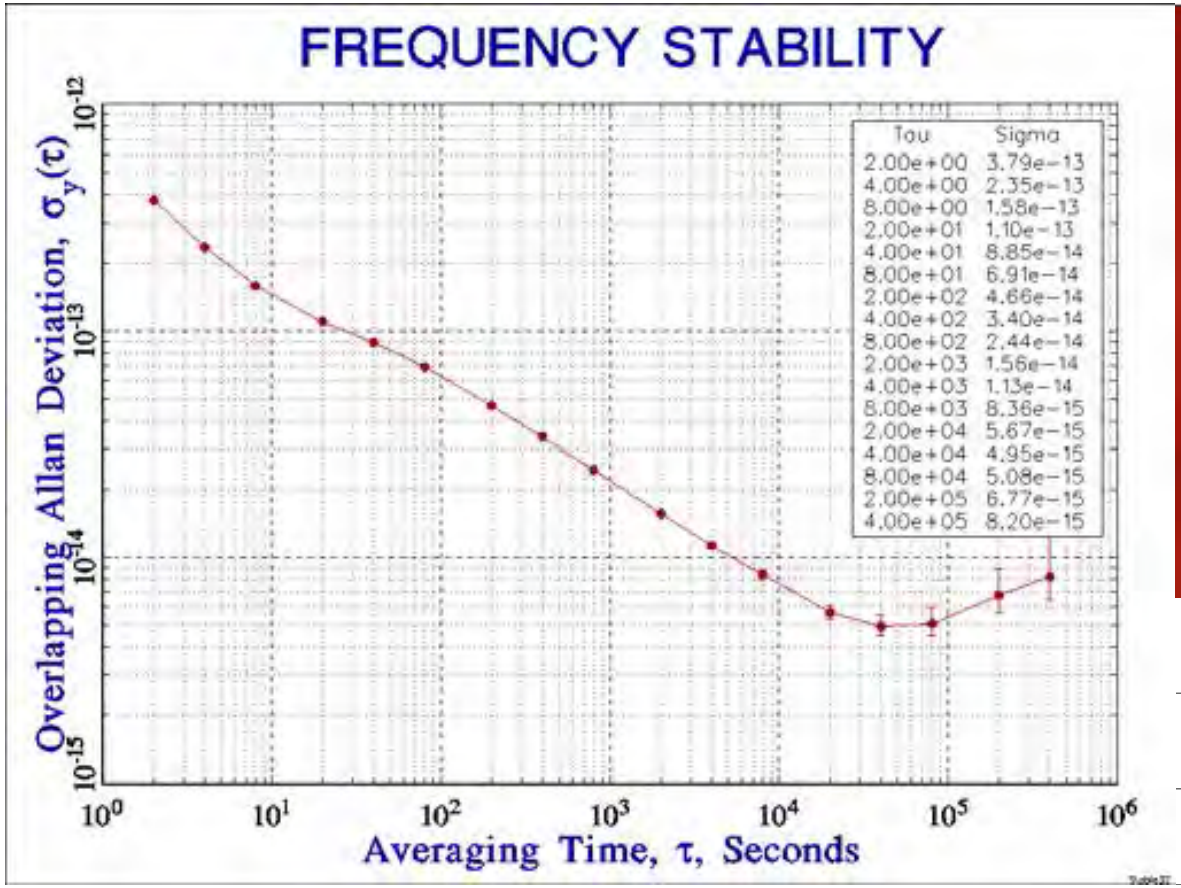
$$\sigma_y(\tau) = \sqrt{\frac{k_s kTF}{2A_c}} \frac{(1+S_0-\alpha)^2}{Q_0 \alpha \sqrt{S_0}(1+S_0)} \tau^{-\frac{1}{2}}$$

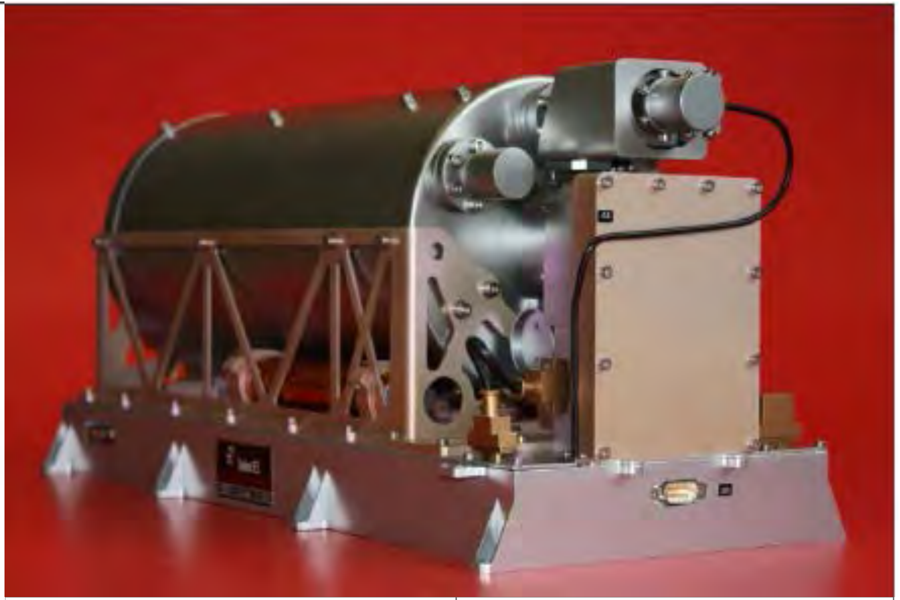
$$\alpha = \frac{\mu_0 \mu_B{}^2 \eta' Q_{lc} I}{\hbar V_b \gamma_1 \gamma_2} \qquad \alpha \cong 0.3 \text{ , So} \cong 0.3$$





MINI-PHM EQM PP MODEL STABILITY TEST

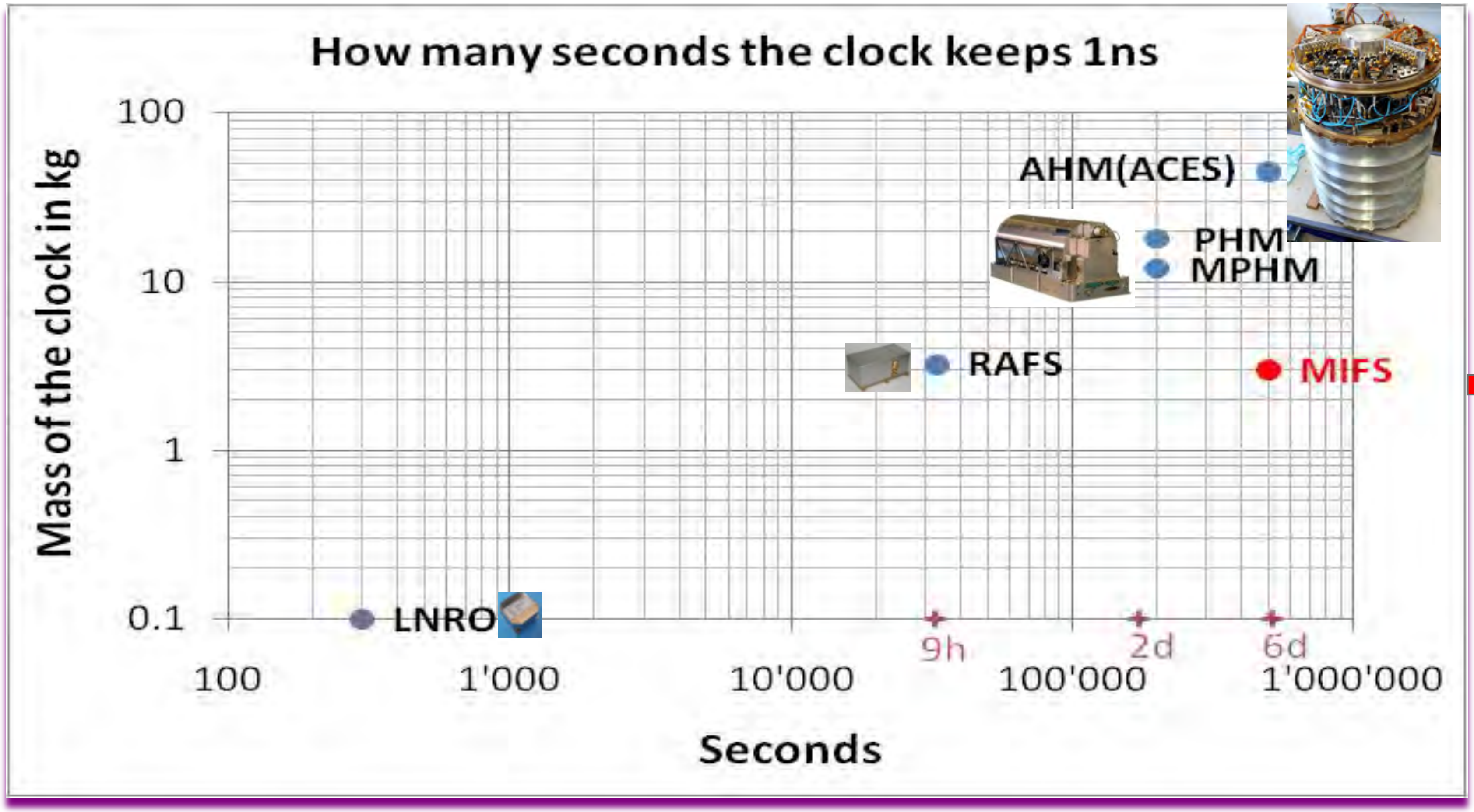




Dimensions	179 x 465 x 175mm
Mass	8Kg
Frequency Drift (/Day)	≤ $1*10^{-15}$ /day

MERCURY ION FREQUENCY STANDARD (MIFS)

Development of Innovative Atomic Clocks for Satellites

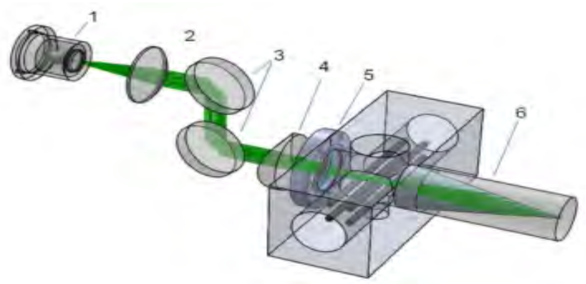


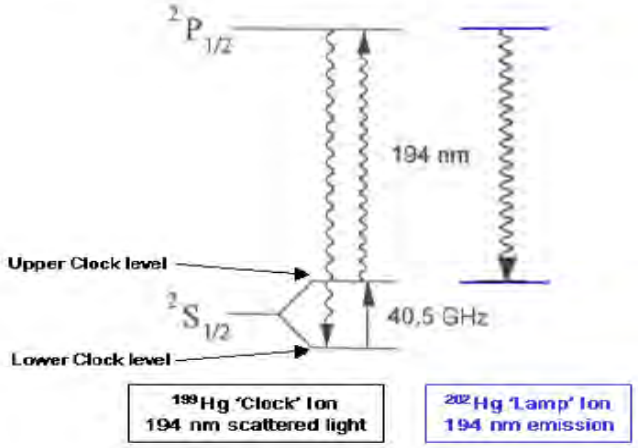
- No Laser
- No Cryogenics
- No Microwave cavities
- No wall collisions, high Q line
- No gas load, not a gas ‘flow-thru‘ architecture, no consumables
- No Light shift!

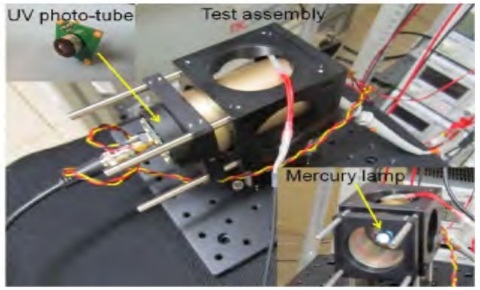
MIFS: PRINCIPLE AND DESIGN

- Based on Mercury lamp ($^{202}Hg^{+}$) optical pumping/detection

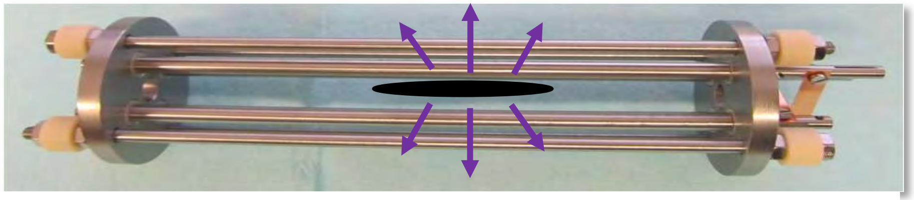
  with a linear trap design optimized for large ion numbers (10^{6} -10^{7} $^{199}Hg^{+}$).
- Clock Transition: 40,507,347,996.8 Hz

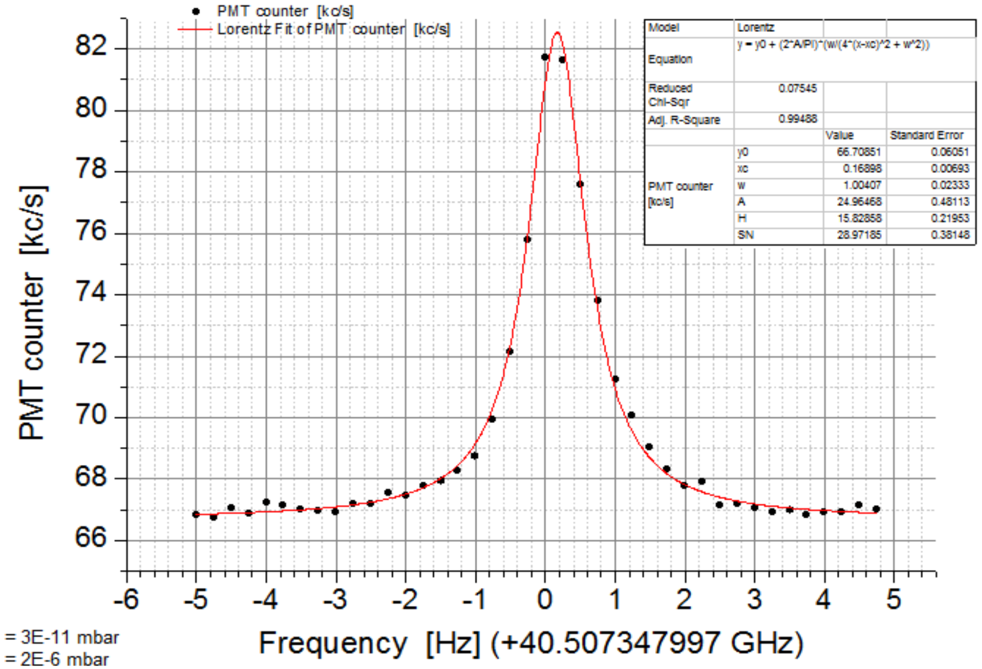






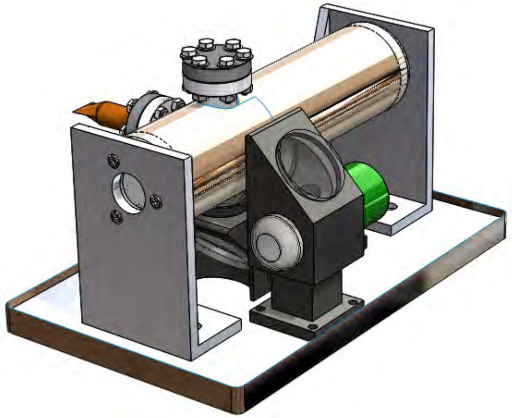
MIFS DEVELOPEMENT



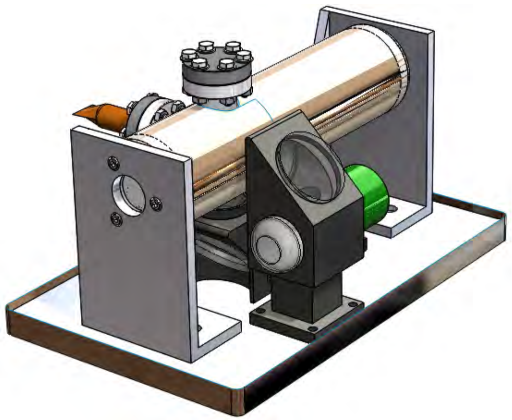


Model	Lorentz		
Equation	y = y0 + (2*A/PI)*(w/(4*(x-xc)^2 + w^2))		
Reduced Chi-Sqr	0.07545		
Adj. R-Square	0.99488		
		Value	Standard Error
PMT counter [kc/s]	y0	66.70851	0.06051
	xc	0.16898	0.00693
	w	1.00407	0.02333
	A	24.96468	0.48113
	H	15.82858	0.21953
	SN	28.97185	0.38148

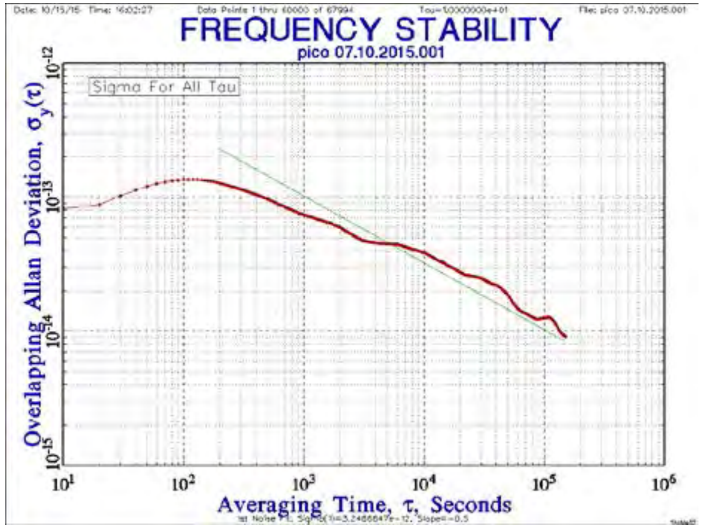
Hg = 3E-11 mbar
Ne = 2E-6 mbar



MIFS DEVELOPEMENT



Parameter		Clock Technology		
	Unit	PHM	RAFS	MIFS (target)
ADEV@1s	-	< 1E-12	3E-12	< 1E-12
ADEV@1d	-	< 5E-15	1E-14	< 1E-14
Frequency drift	1/day	<1E-15	< 1E-13	< 1E-15
Magnetic sensitivity	1/G	< 3E-13	< 1E-13	< 1E-14
Thermal sensitivity	1/°C	< 3E-14	< 3E-14	< 1E-15
Volume	litre	28	2.5	< 5
Mass	kg	18	3.4	< 5
Power	W	60	< 35	< 30
Lifetime	years	12	> 15	> 15
Time to 1 ns error	days	2	0.3	10



GNSS ONBOARD CLOCKS ENSEMBLE

GNSS ONBOARD TIMING SUBSYSTEM

Critical payload of Global Navigation Satellite System, consisting of

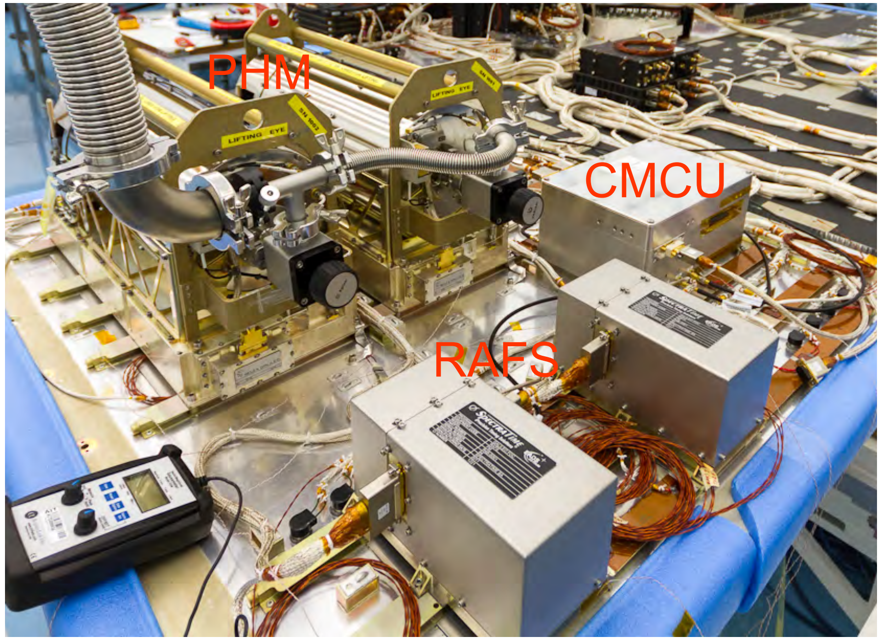
- Ultra-stable on-board atomic clocks
- Clock Monitoring and Control Unit (CMCU)

> Direct impact on navigation system performance through contributions of system ranging error and availability

1st generation of Galileo satellites

- 1 x Master: PHM
- 1 x Hot redundancy: RAFS
- CMCU selects the clock signal to be distributed

> Vulnerabilities and risks



Next generation

> Stability, robustness , reliability

Source: SSTL

ONE CLOCK ENSEMBLE (ONCLE)

A concept of the ONCLE for a robust time and frequency reference system proposed by Spectratme in 2009.

- **Improved robustness and performances**

  Advanced processing in real time with min. 3 input clocks

  - Clock Ensemble based on weighted averaging
  - Clock Fault Detection & Correction based on a cascade of low-pass recursive filters & associated logic
  - Steering loop to keep all clocks in phase and frequency

- **Simple and reliable**

  - Possibly implemented into single RAD-HARD FPGA

DEVELOPMENTS UNDER EGEP

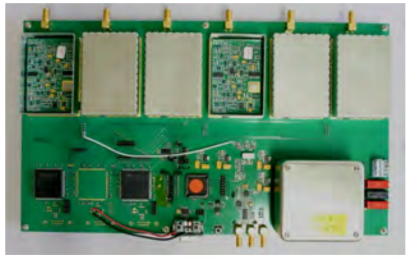
European GNSS Evolution Programme (EGEP)

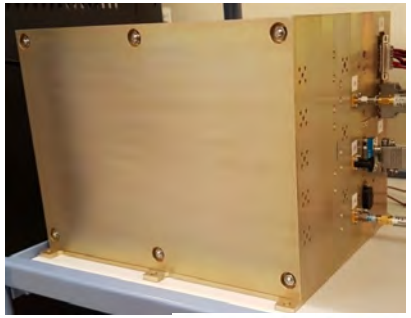
- 2012 – 2014: Robust On-board Frequency Reference Subsystem (FRS), Elegant Breadboard

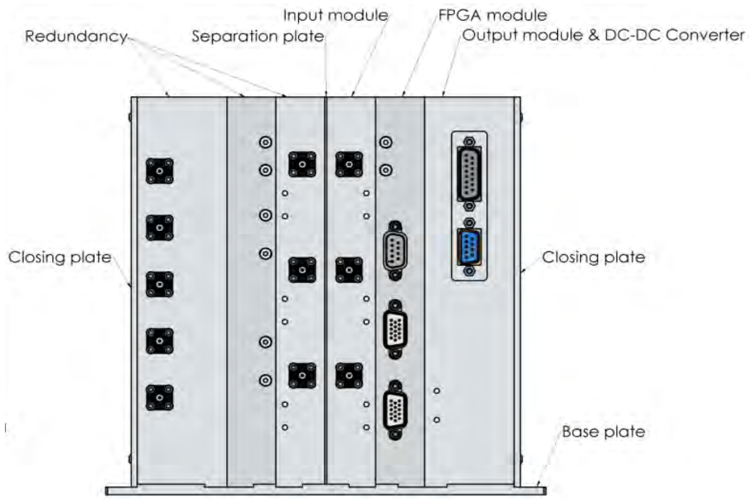
  > Feasibilities of HW & Algorithms approaches demonstrated

- 2015 – 2019: On-board Clock Ensemble CMCU (CMCU+), Engineering Model

  > 50% contributions from Orolia (Spectratime)
  - ✓ *HW: Output module (inc. LNMO), DC-DC Converter, Box mechanics*
  - ✓ *Algorithms: design, development , high-level verification tests*

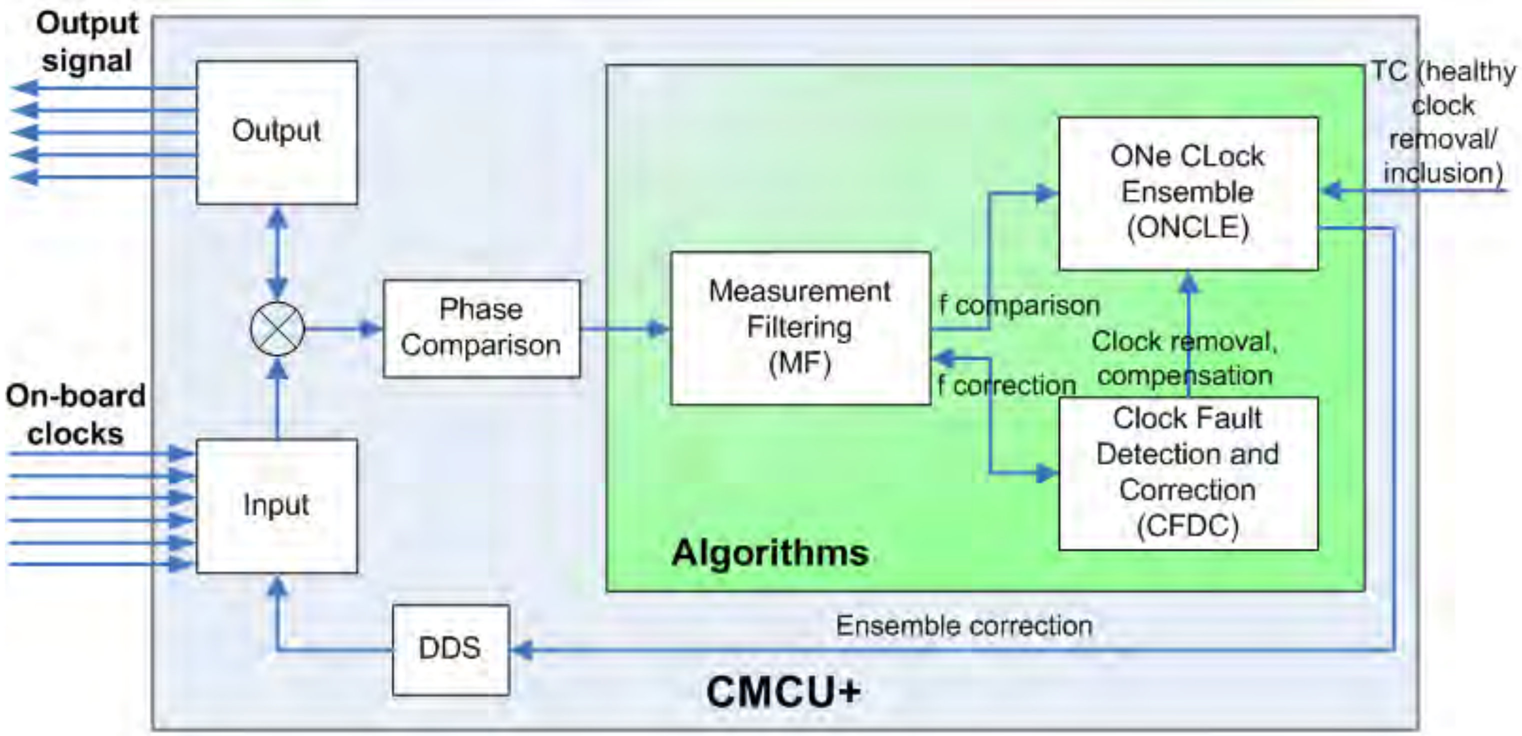






ALGORITHMS DESIGN

CMCU+ architectures and algorithms functions



Algorithm architecture based on FRS development, adapted with CMCU HW architecture

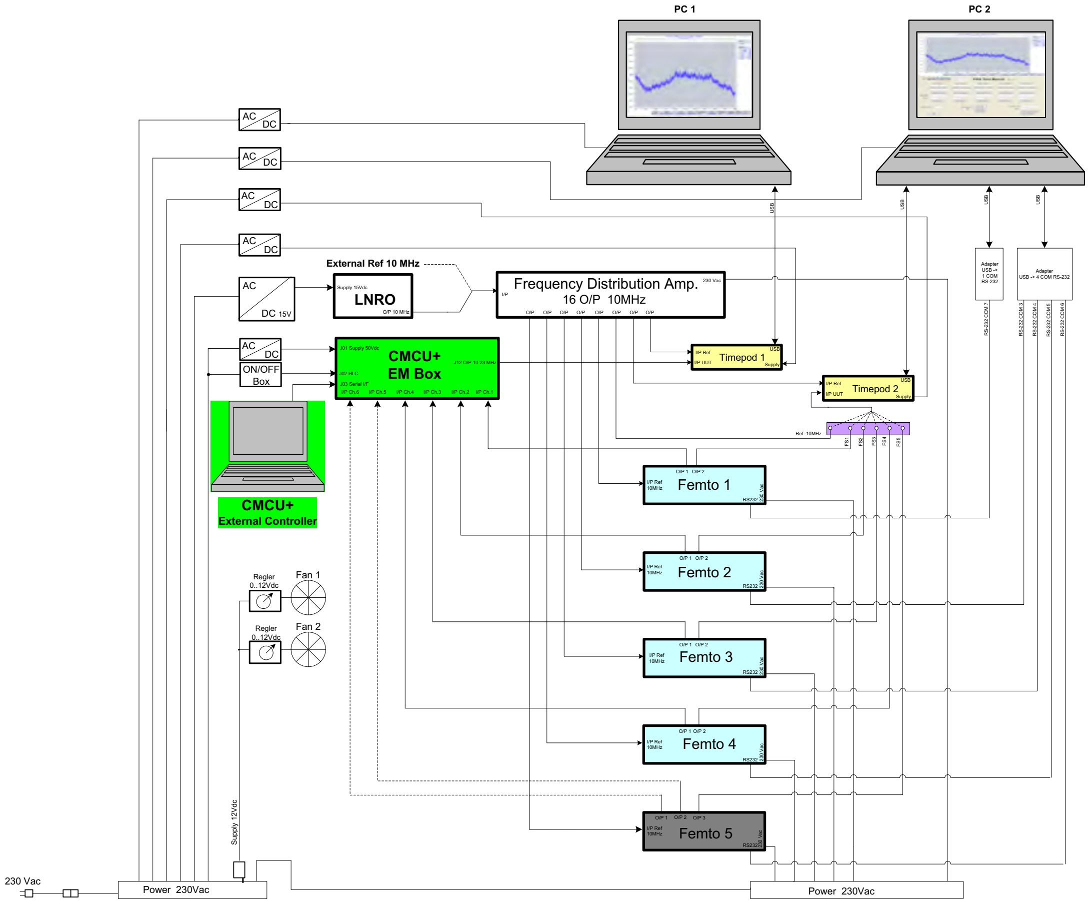
VERIFICATION METHOD

Algorithms design verified successfully by simulation under various test cases with 3 clock sets including clock events on master and secondary clocks

High-level performance verification conducted at CMCU+ EM level

- Real-time operation
- 2 sets of clock configurations (atomic clock technology diversity)
  - ✓ Set A: 1 x PHM + 3 x RAFS
  - ✓ Set B: 3 x PHM + 1 x RAFS
- Test results verified by
  - ✓ Clock handling capability
  - ✓ ADEV
  - ✓ Maximum Accumulated Phase Offset (MAPO)

CMCU+ TEST SETUP



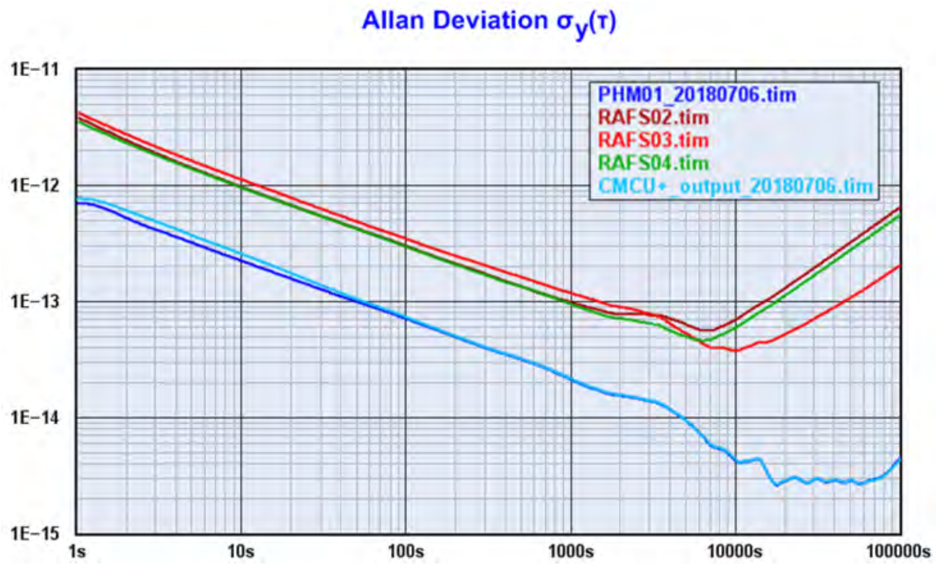
Testing and validation tool

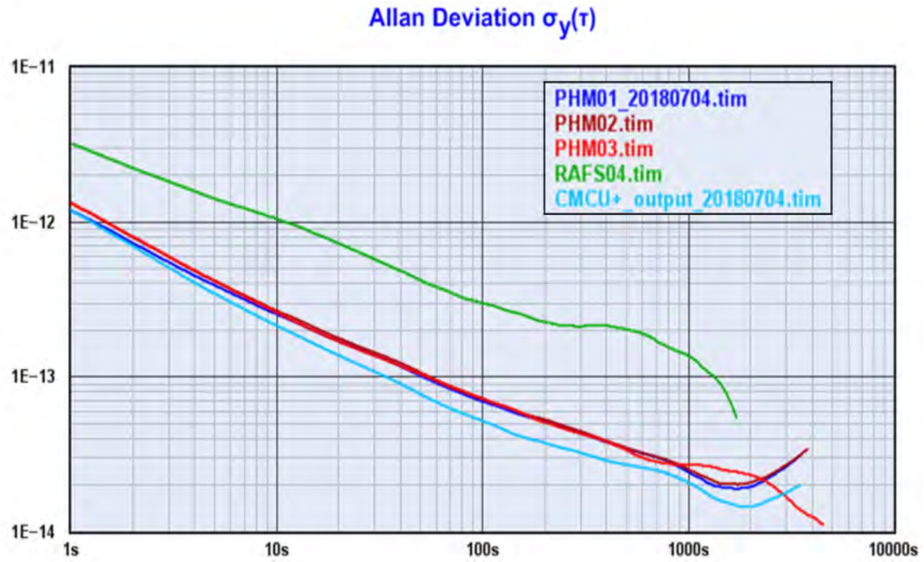
iTest® FemtoStepper

- ✓ Ability to ‘REPLAY’ clock data
- ✓ Generate clock anomalies
- ✓ High resolution : 100 fs, 1e-17

TEST CASE: ENSEMBLE STATIONARY PERFORMANCE

> Two AFS Sets, two data sets: 2-day per 1s; 4-hour per 0.1s





> *Output ADEV:*

Set A *Equivalent as Master PHM*

Set B *At 1s, equivalent as PHM, impacted by PLL*

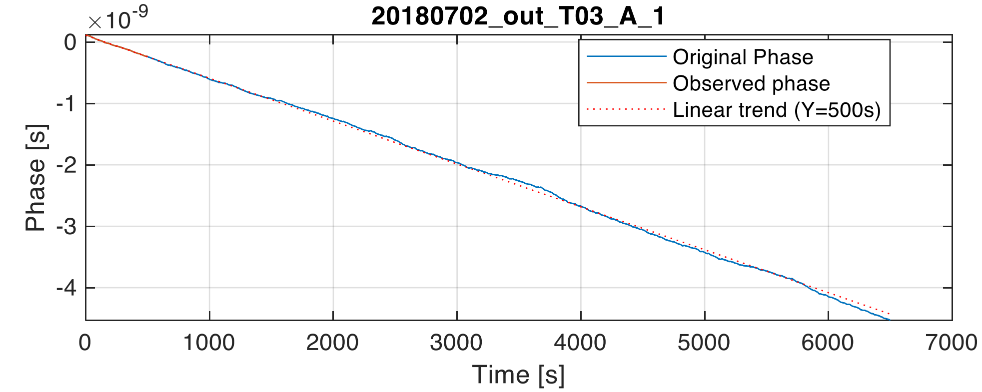
At ≥ 10s: 1/√3 of ADEV of PHM

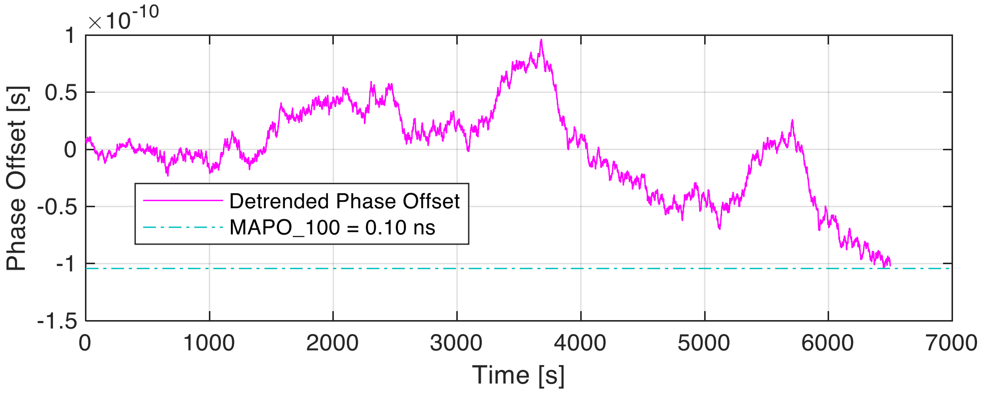
spectratime
an Orolia brand

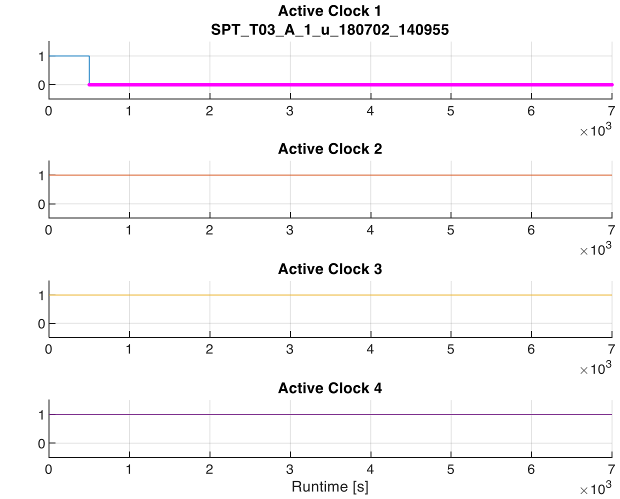
orolia

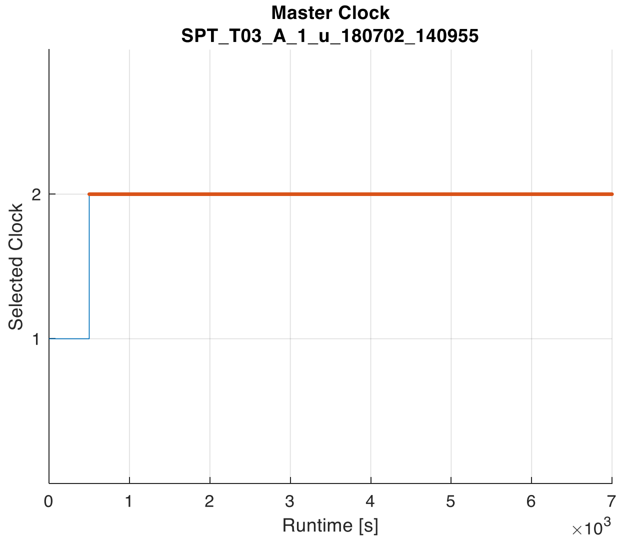
TEST CASE: HEALTHY AFS REMOVAL BY COMMAND_A (MASTER)

> PHM01: Removal at 500s





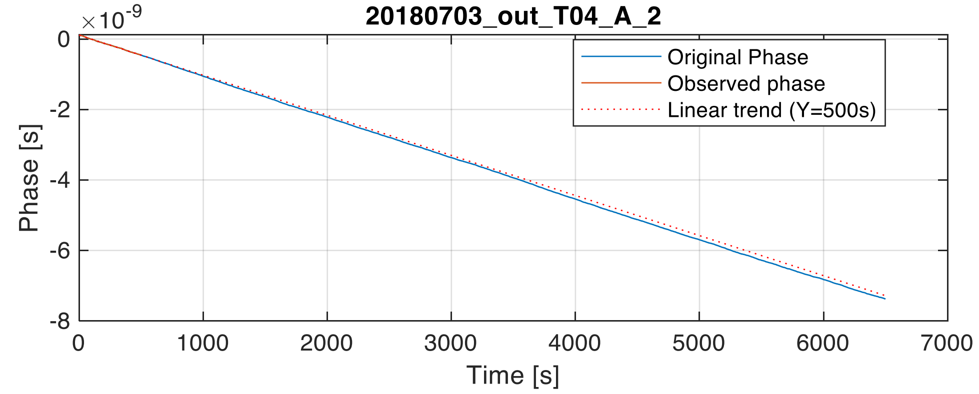


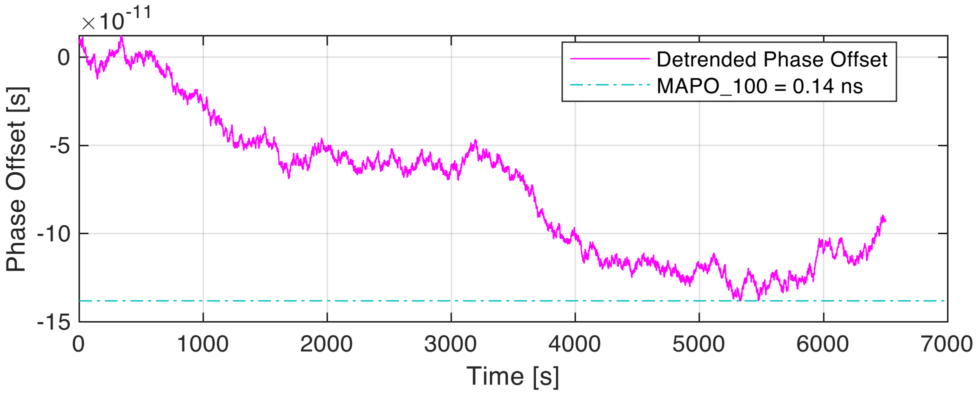


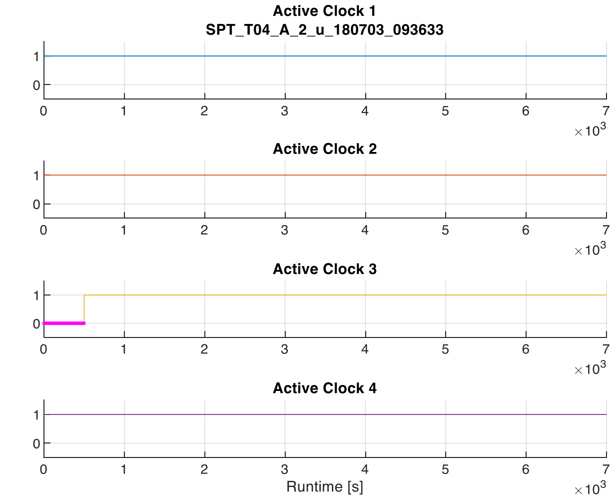
> PHM01 removed and smoothly switched over

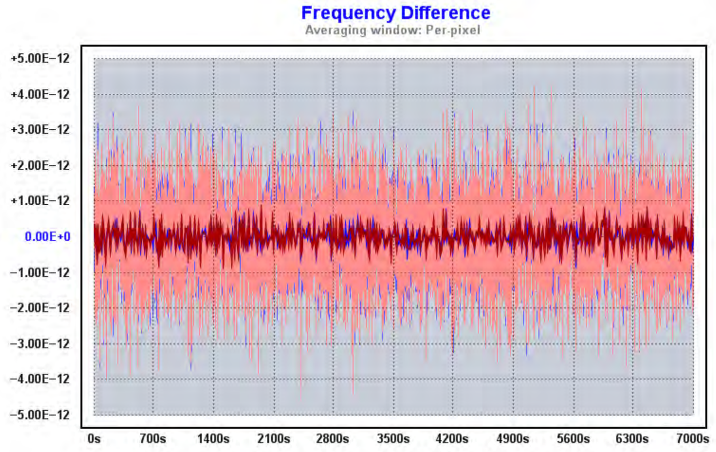
TEST CASE: HEALTHY AFS INCLUSION BY COMMAND_A (SECONDARY)

> RAFS03: Included at 500s







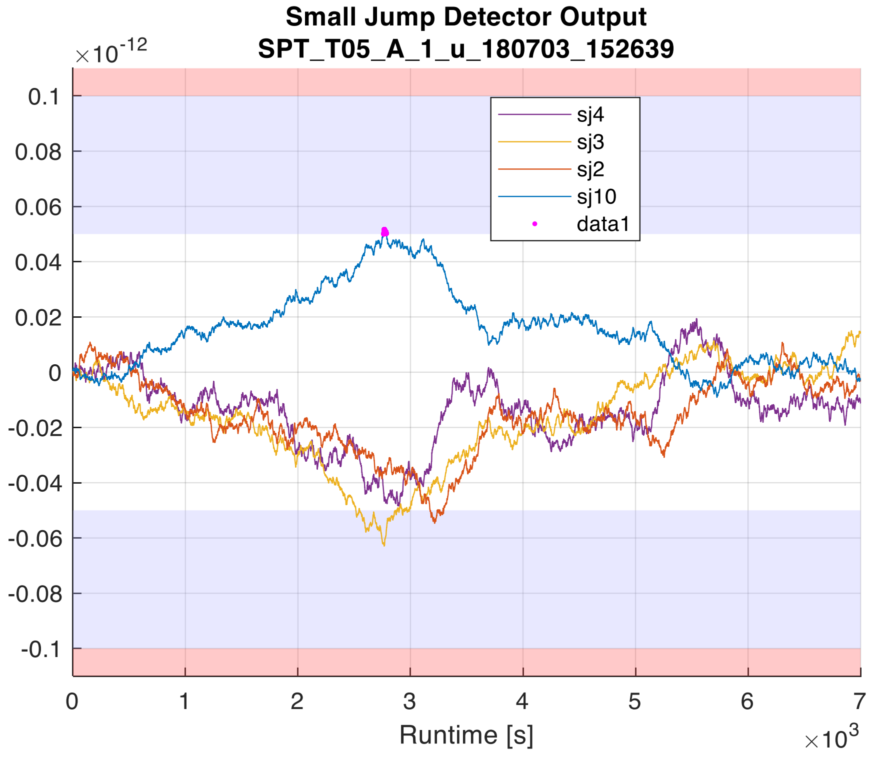


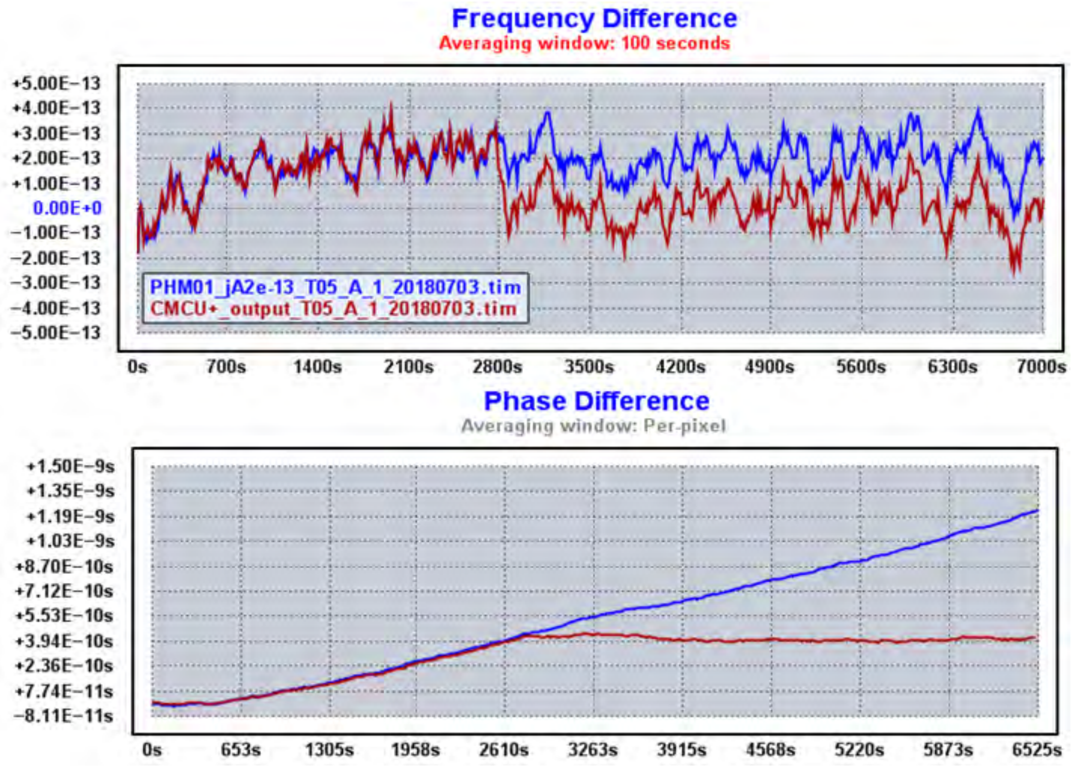
Filename	Sample Interval	Duration
20180703_PHM01_1s_I60_T04_A_2.tim	0.500 s	1h 56m 40s
20180703_out_T04_A_2.tim	0.500 s	1h 56m 40s

> RAFS included w/o impact on output

TEST CASE: HIGH-DYNAMICS FREQUENCY JUMP_A (MASTER)

> Input PHM01: f jump=2e-13 ~ MAPO_100=1.22ns

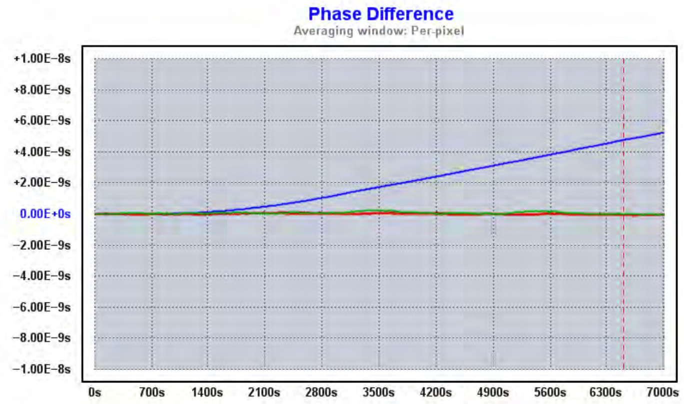




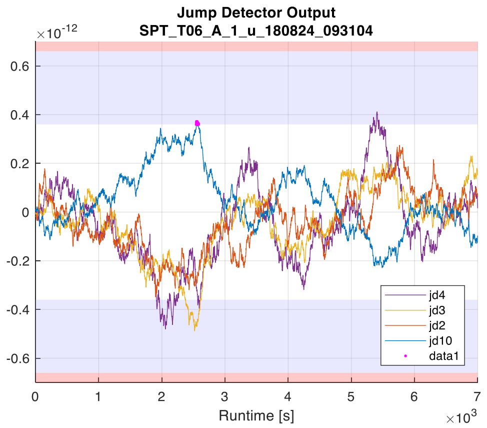
> CMCU+ output: f jump corrected by SJ ~ MAPO_100=0.45ns

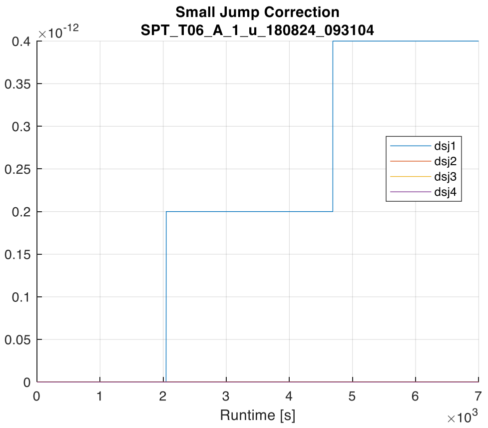
TEST CASE: MEDIUM-DYNAMICS FREQUENCY JUMP_A (MASTER)

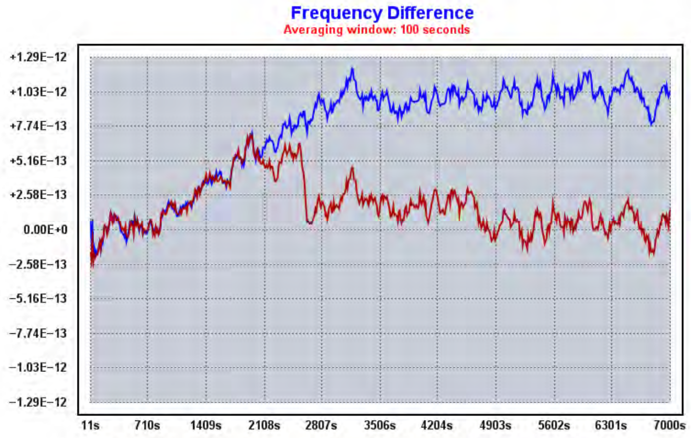
> Input PHM01: f jump=1e-12 during 2500s ~ MAPO_100=4.8ns



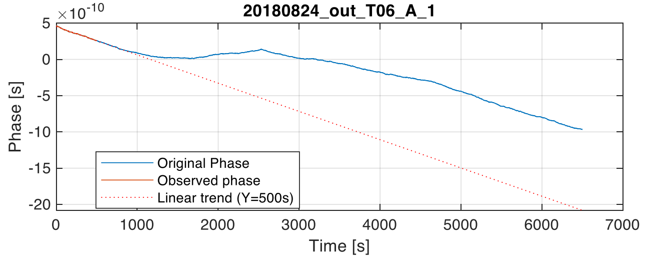
Filename	Sample Interval	Phase at 6501s	Duration
PHM01_jB1e-12y_1s_7000s.tim	1 s	4.77E−9s	1h 56m 40s
RAFS02_1s_7000s_0.tim	1 s	−6.21E−11s	1h 56m 40s
RAFS03_1s_7000s_0.tim	1 s	−8.30E−11s	1h 56m 40s
RAFS04_1s_7000s_0.tim	1 s	−8.38E−12s	1h 56m 40s

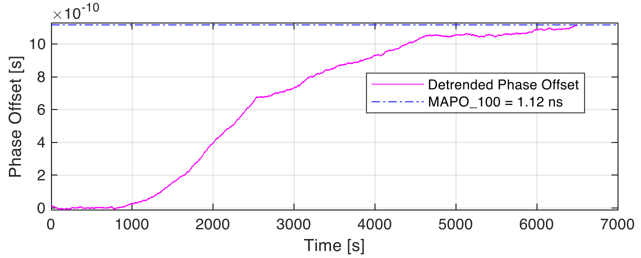






Filename	Sample Interval	Duration
20180824_PHM01_jB1e-12y_T06_A_1.tim	0.500 s	1h 56m 40s
20180824_out_T06_A_1.tim	0.500 s	1h 56m 40s

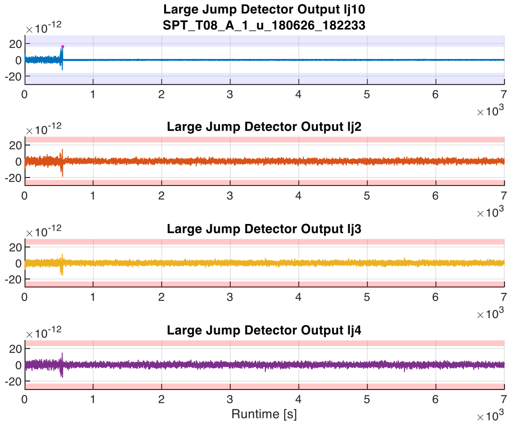


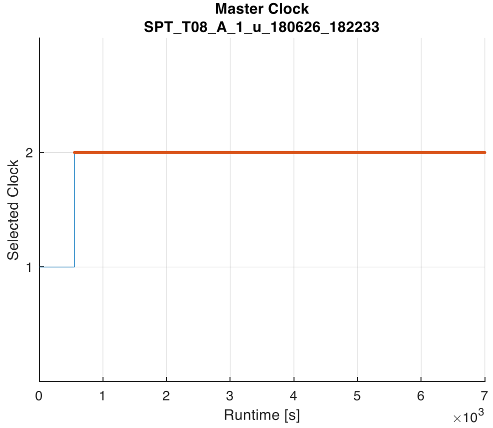


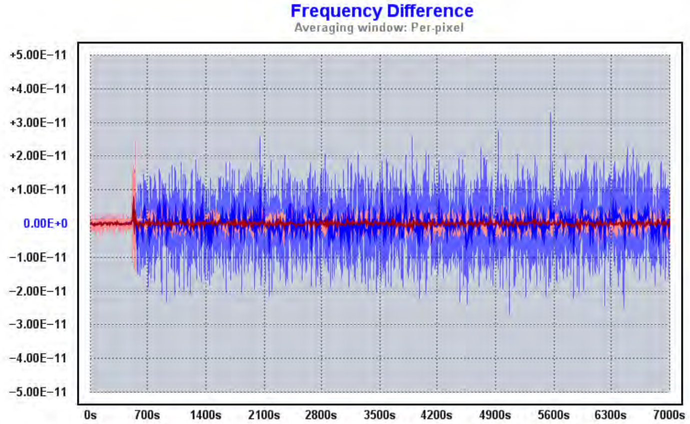
> CMCU+ output: f jump corrected by JD&SJ ~ MAPO_100=1.12ns

TEST CASE: WFN LEVEL INCREASE_A (MASTER)

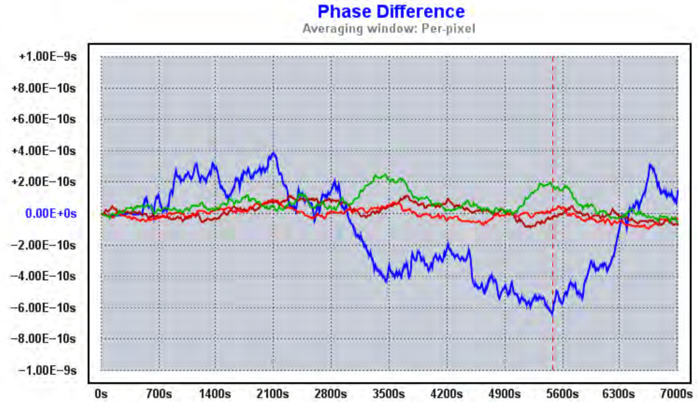
> Input PHM01: 10xWFN



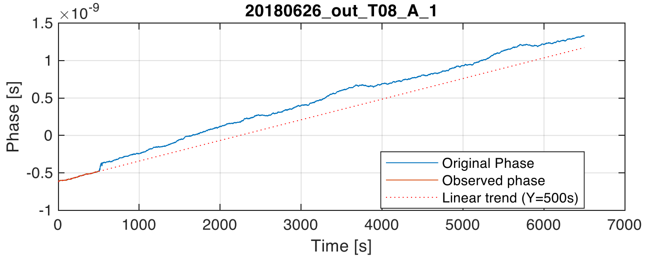


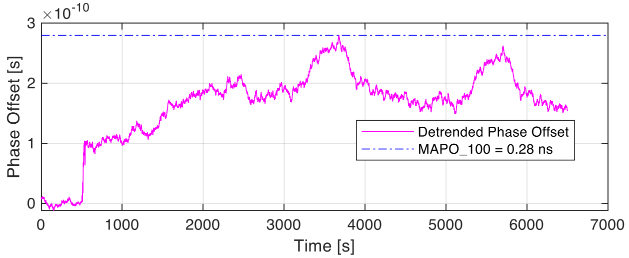


Filename	Sample Interval	Duration
20180626_PHM01_WFD10_1s_I60_T08_A_1.tim	0.500 s	1h 56m 40s
20180626_out_T08_A_1.tim	0.500 s	1h 56m 40s



Filename	Sample Interval	Phase at 5480s	Duration
PHM01_WFD10_1s_7000s.tim	1 s	−6.42E−10s	1h 56m 40s
RAFS02_1s_7000s_0.tim	1 s	−2.54E−11s	1h 56m 40s
RAFS03_1s_7000s_0.tim	1 s	2.97E−11s	1h 56m 40s
RAFS04_1s_7000s_0.tim	1 s	1.77E−10s	1h 56m 40s

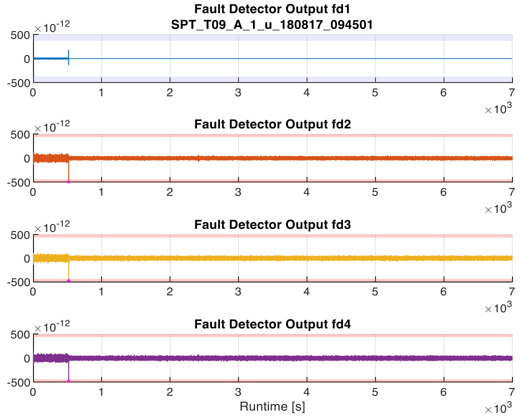


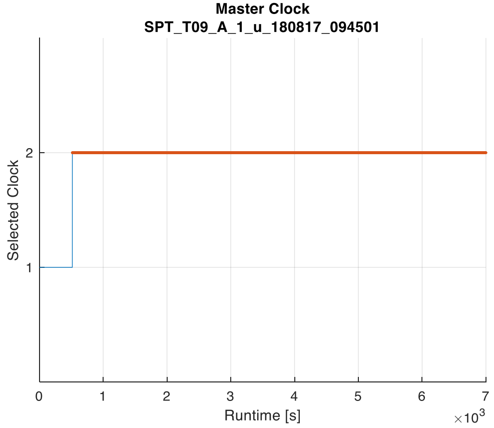


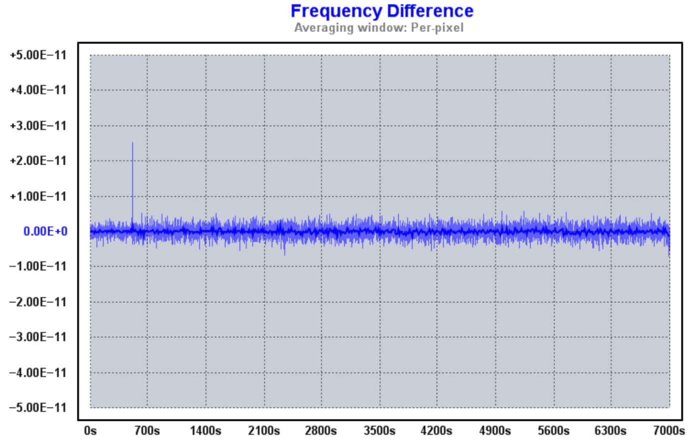
> CMCU+ output: f jump corrected by JD&SJ ~ MAPO_100=0.28ns

TEST CASE: FAILURE JUMP_A (MASTER

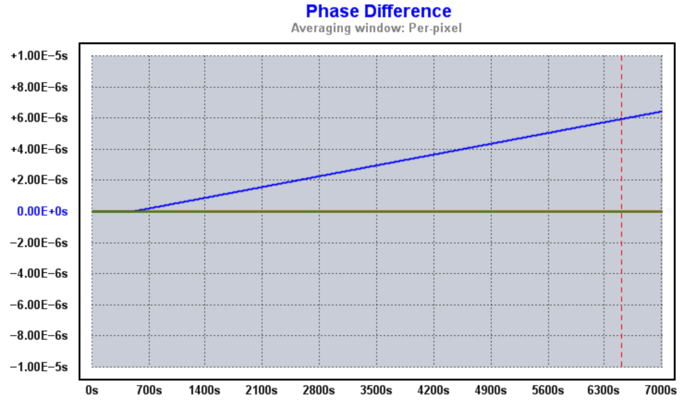
> Input PHM01 failure jump 1e-10 ~ MAPO_100=6µs



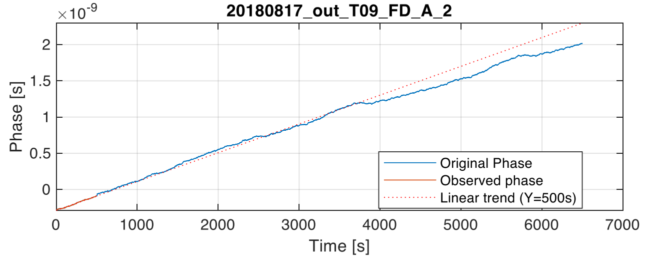


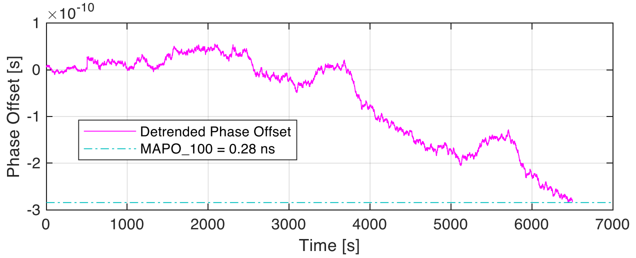


Filename	Sample Interval	Duration
20180817_out_T09_FD_A_1.tim	0.500 s	1h 56m 40s



Filename	Sample Interval	Phase at 6501s	Duration
PHM01_jA1e-9_1s_7000s.tim	1 s	5.94E−6s	1h 56m 40s
RAFS02_1s_7000s_0.tim	1 s	−6.21E−11s	1h 56m 40s
RAFS03_1s_7000s_0.tim	1 s	−8.30E−11s	1h 56m 40s
RAFS04_1s_7000s_0.tim	1 s	−8.38E−12s	1h 56m 40s





> Failed Master PHM detected by FD, removed and switched over ~ MAPO_100=0.28ns

CONCLUSIONS

Direct Results

- Algorithms designed, developed, and verified by an extended test and validation campaign
- Functionalities and performances verified successfully with improved robustness and timing accuracy
- A smart, robust and feasible solution for a spaceborne implementation
- Benefits for on-board timing sub-system for 2nd Generation of Galileo satellites (G2G)

Next

- Further tuning of parameters
- To be implemented into fully flight hardware
- Configurability and flexibility of operation

spectratime
an Orolia brand

MINIATURE CLOCKS

FOR FUTURE LEO –PNT SATELLITES

orolia

MINI RUBIDIUM: PROJECT GOAL & APPLICATIONS

- → High stability frequency source
- → Telecom & mobile network synchronization (TDM, PTP)
- → Military airborne, ground, mobile & unmanned radio communications
- → Oil & gas sensor-based exploration
- → Instrumentation
- → Portable & battery-sensitive applications
- → GPS-based applications

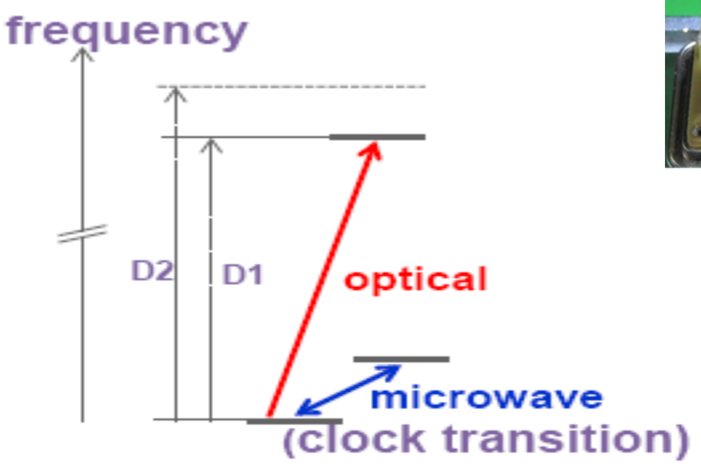
Frequency	10 MHz
Temperature range	-5°C to 55°C
Frequency change over Temp. range	<= 2E-10
Short term stability	1.5E-10 @ 1s
Aging (after 3 month)	< 2E-12 / day

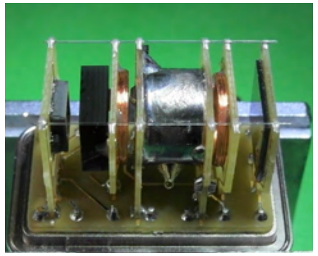
Size	52.2 × 52.2 × 19.5mm.
Weight	90 g max.
Volume	< 50 cc
Power	0.4 W

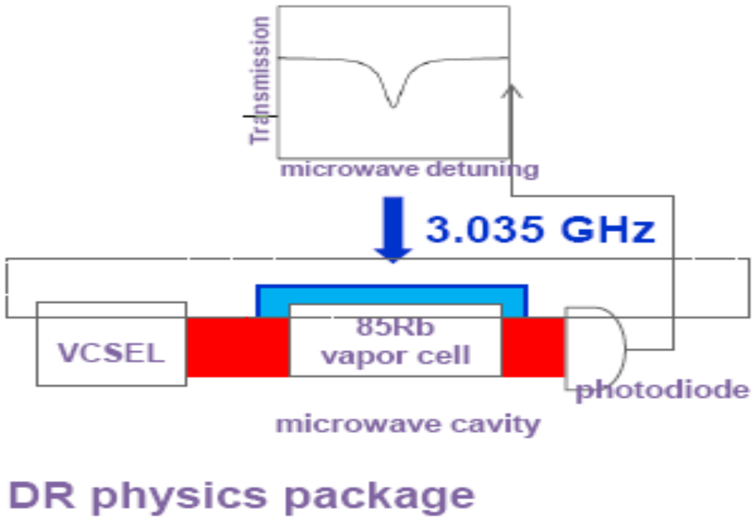
DOUBLE-RESONANCE PHYSICS PACKAGE

Schematic of the laser pumped double resonance (D1) physics package

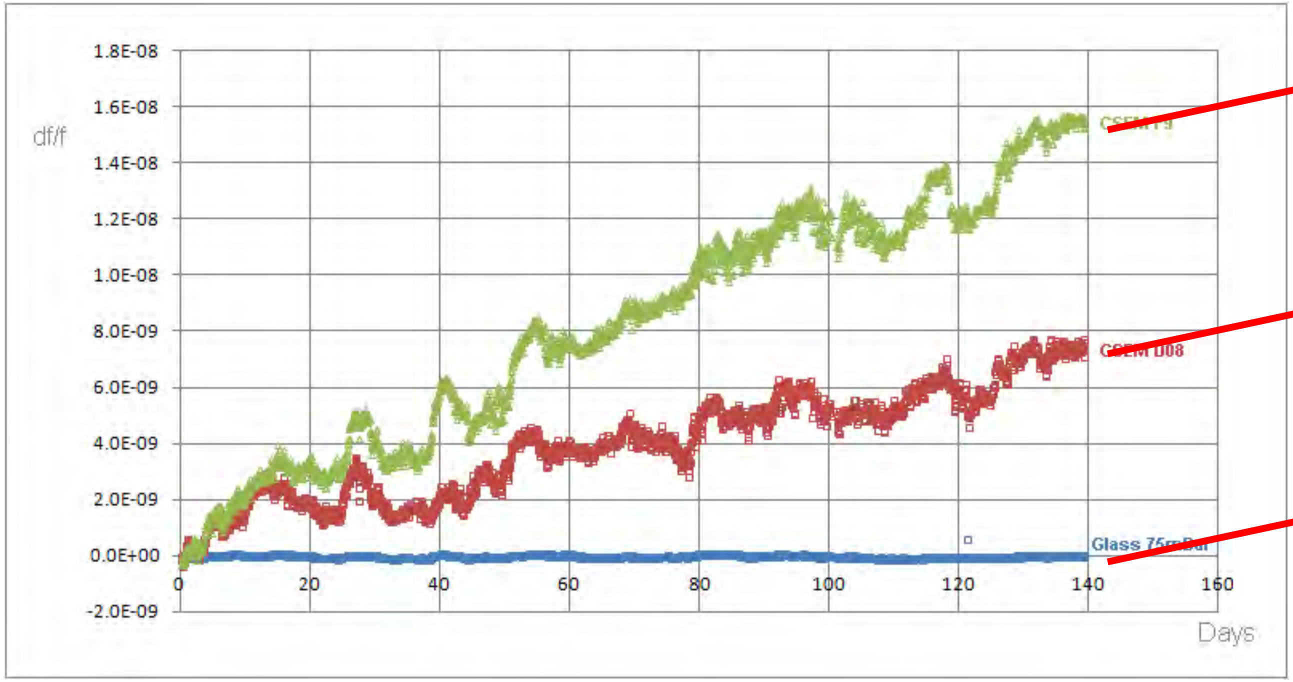
- (+) Less constraints on laser (No RF modulation)
- (+) No need taking care of light polarization
- (+) Laser amplitude & frequency drift can be compensated
- (+) With new patented technique , less RF power is necessary and no size limitation







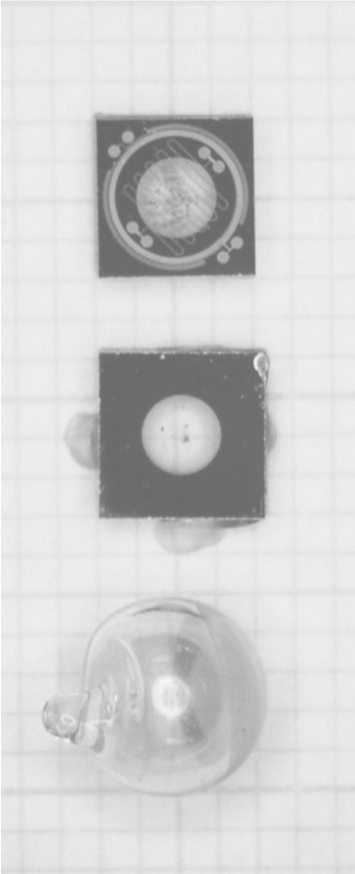
NEW MINIATURE RUBIDIUM CLOCK : DRIFT RATES



MEM1

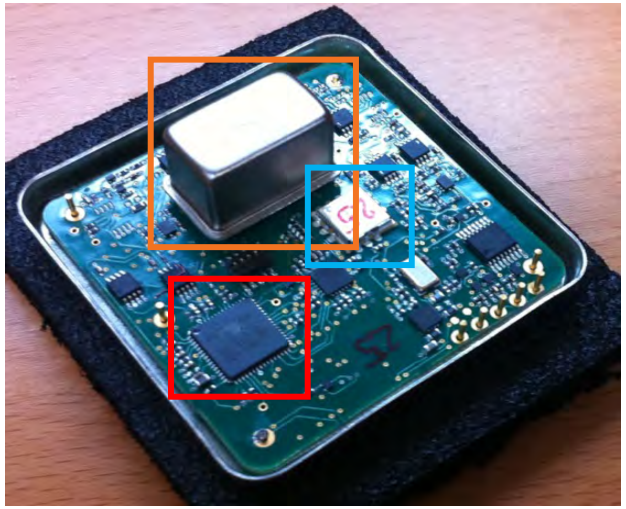
MEM2

Glass

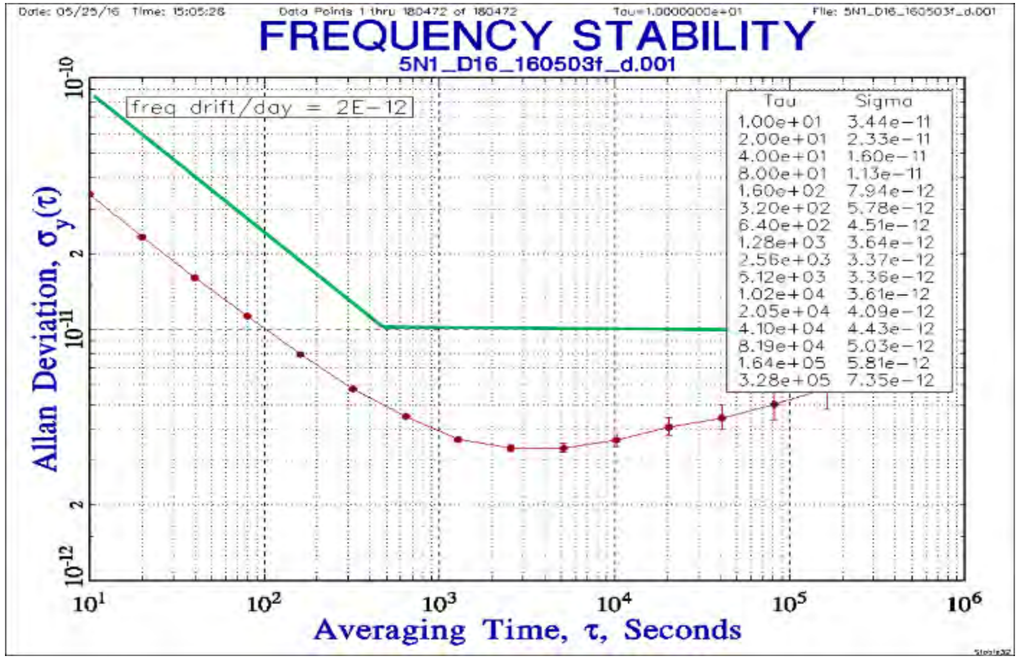


MINI RUBIDIUM: PRODUCTION STATUS

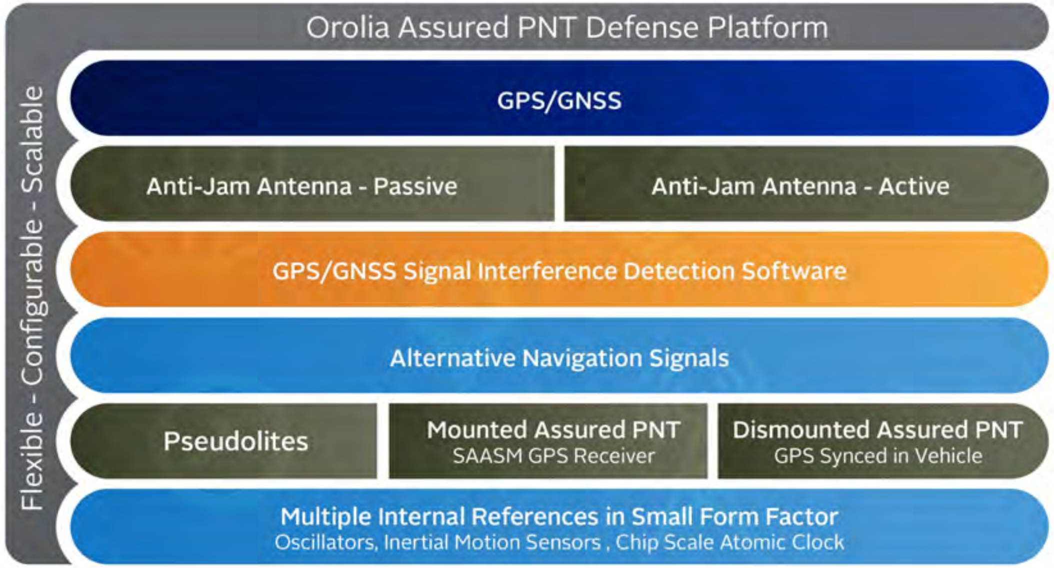
2016 - 2017	Preparation of 50 mTS units for test-campaign
2018 -	Pre-production units to be shipped to selected clients Successfull passing radiations testing fully suitable for LEO satellites applications (LEO PNT)



- Physics Package (DIL-14)
- VCO @3GHz
- DSP micro-processor



MOBILE PNT – MRO50 APPLICATIONS



VersaSync

Next Generation Resilient Time and Frequency Source

VersaPNT

Rugged Position, Navigation and Timing

THANK YOU
FOR YOUR ATTENTION

spectratime
an Orolia brand

orolia