Navigation Systems Clocks Technologies

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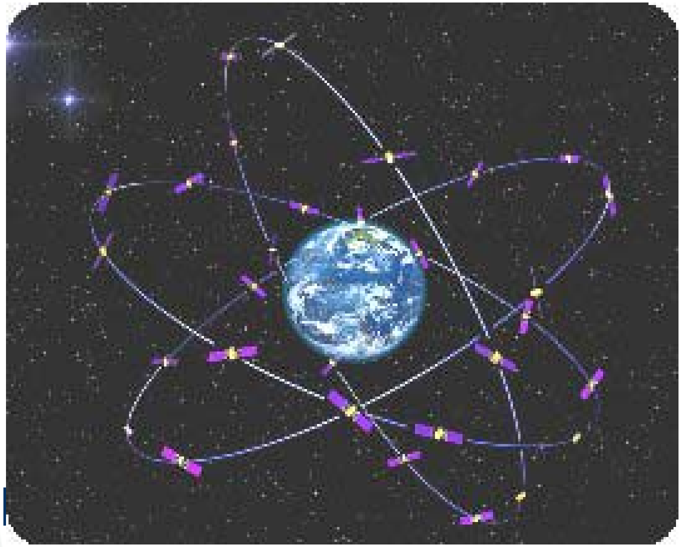
Presentation Outline

1. Development Steps , Performances and Status of the Galileo Space Clocks
2. Evaluation of the accuracy of the Space Clocks taking into account measurement noise induced by geodetic technique in measuring and predicting the Space Clocks
3. On board Galileo Time Keeping
4. On ground system clock generation
5. Conclusions

Galileo program description

- Global Navigation Satellite System Jointed by EC & ESA
- Constellation
  - 30 satellites
  - 3 circular MEOs
  - Altitude 23222km
  - Inclination 56°
- Mission life time of 12 years
- Clock model update < 10'000 sec.(TI
- Metric/sub-metric navigation accuracy -→ 1 to 3 ns clock model error



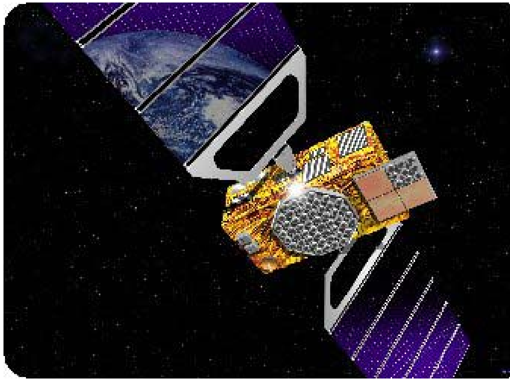
Onboard Clocks for Galileo Development History

- Two baseline clock technologies
  - Rubidium Atomic Frequency Standard(RAFS)
  - Passive Hydrogen Maser (PHM)
- Long heritage for both clocks in Switzerland since ’80s
- Continuous support from ESA & Swiss Space Office especially since set-up of the GNSS2 program

In-progress GSTB-V2

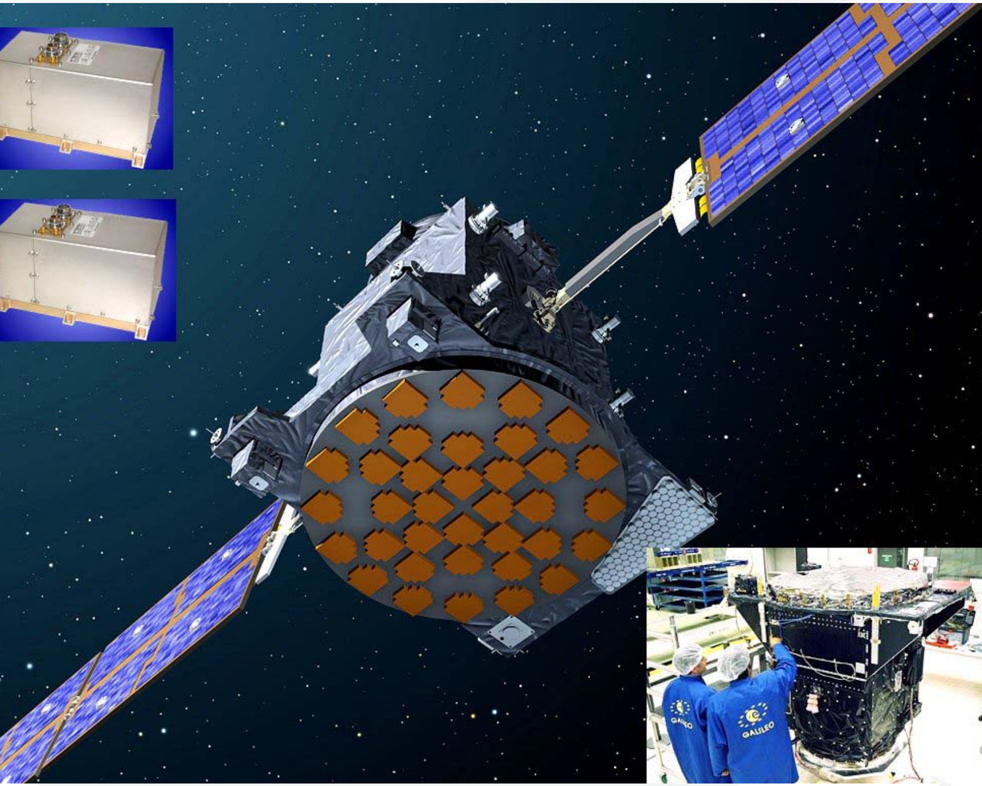
First Flight Opportunity for Galileo Clocks Validation !

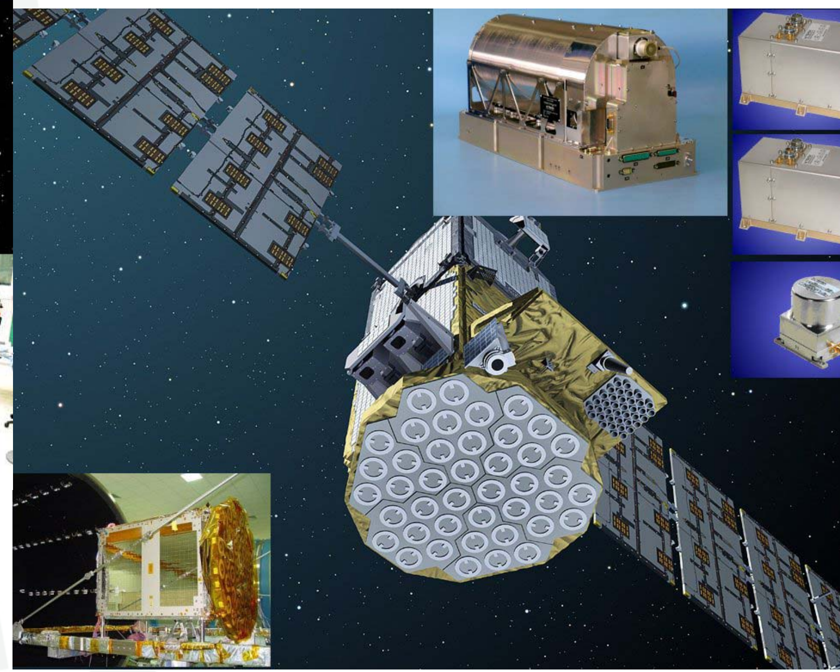
- Two experimental satellites due for launch end of 2005 & 2006 for:
  - Frequency Filling
  - Test of critical technologies (like clocks)
  - Experimentation on Galileo Signals
  - Characterisation of MEO environment



- Navigation Payload embarking
  - One PHM unit and two RAFS units (GIOVE-B)
  - Two RAFS unit (GIOVE-A)

GIOVE Satellites

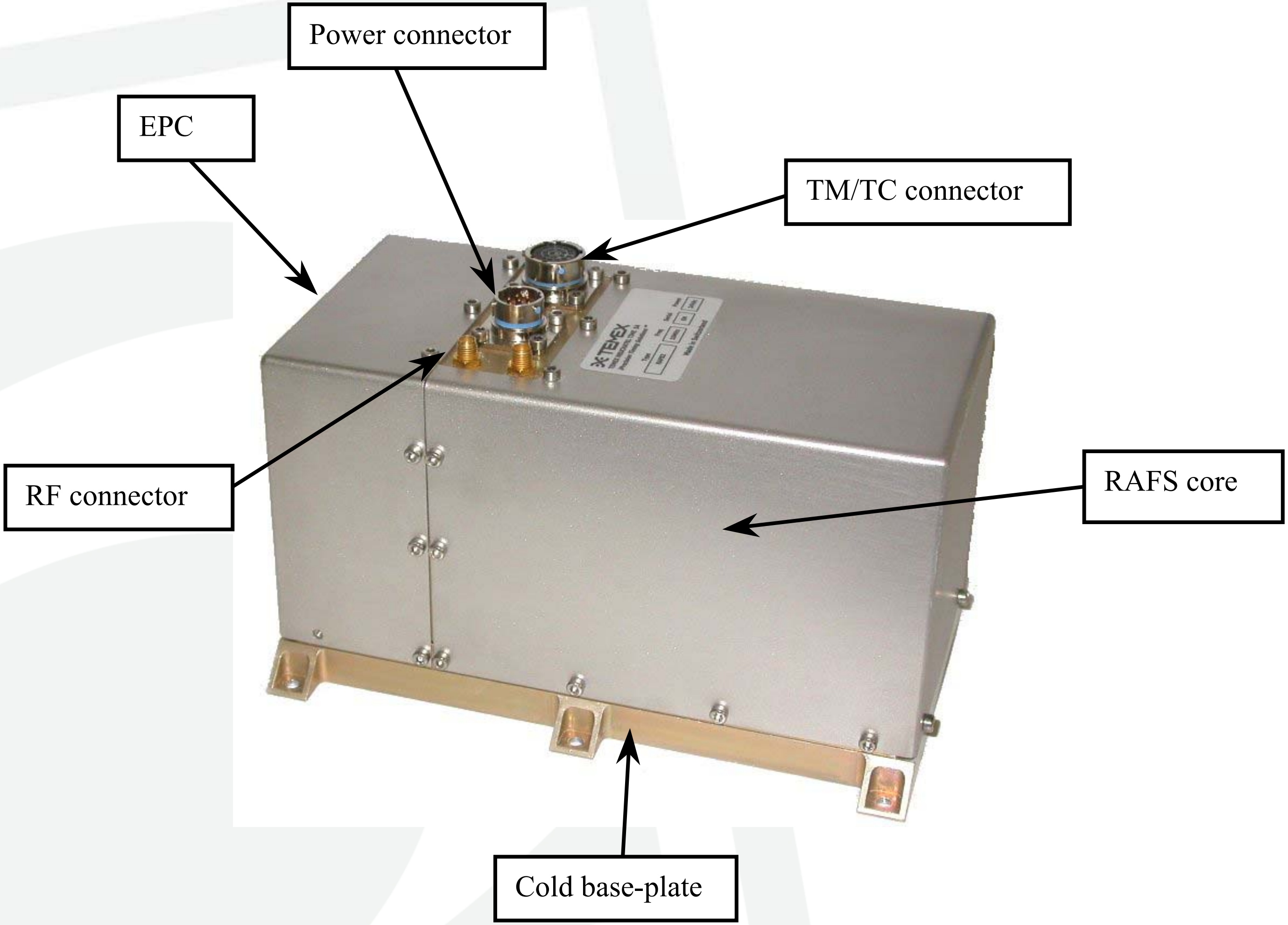




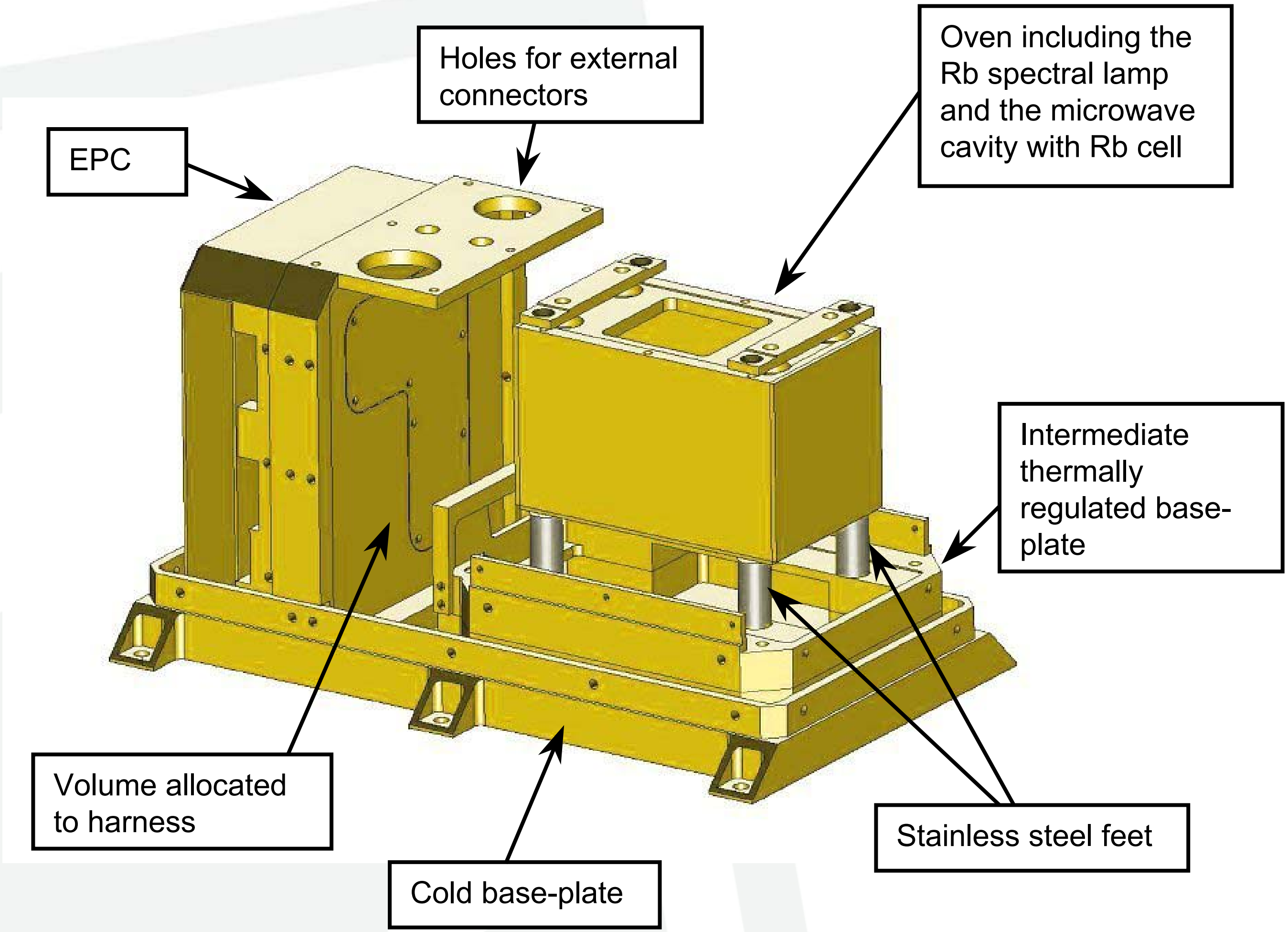
Development Milestones

teps	RAFS	SPHM	OPCs
B	completed in 1995	Based on VREMYA design +ON/GA analysis (1999)	$< 3E\text{-}12*\tau^{-1/2}$ on gnd Cs OP tube in 2002
M	Completed in 2000	Completed by Q2 / 2003 by ON&GA	Will start in Thales in 2006
QMs	5 models in specs in 2002 Lifetime still on-going	Industrialisation and EQM Completed by Q4/2003 by GA&TNT	-----------
M	Qual. Tests completed Rad test (CNES) Q1/2003	Qualifications in 2006	-----------
Ms or FMs	6 models delivered for Giove A & Giove B Satellites in 2005	Three models delivered for Giove B in 2005 - 2006	-----------

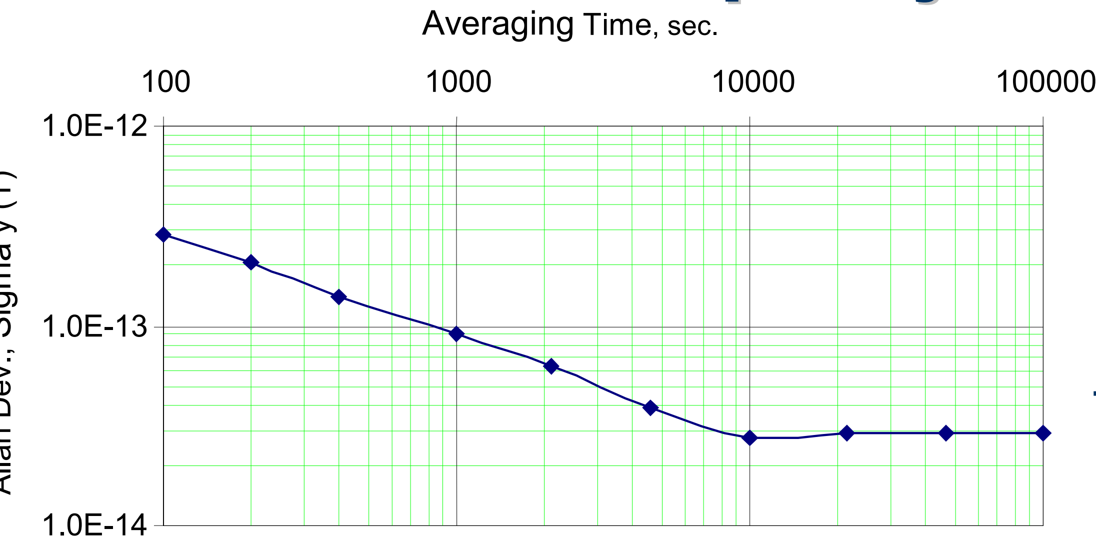
RAFS for GIOVE_A



RAFS internal construction

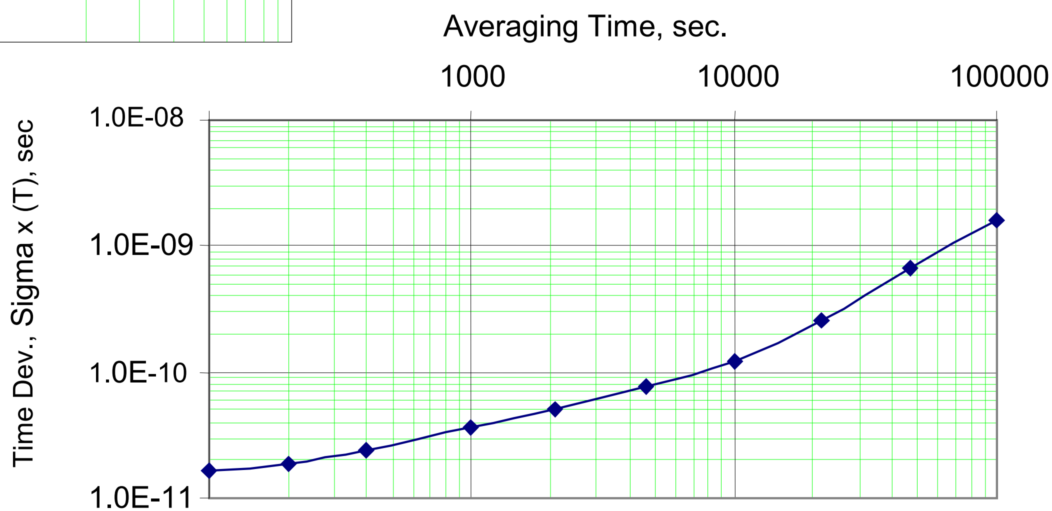


Performance Achieved
RAFS: Frequency & Time Stability

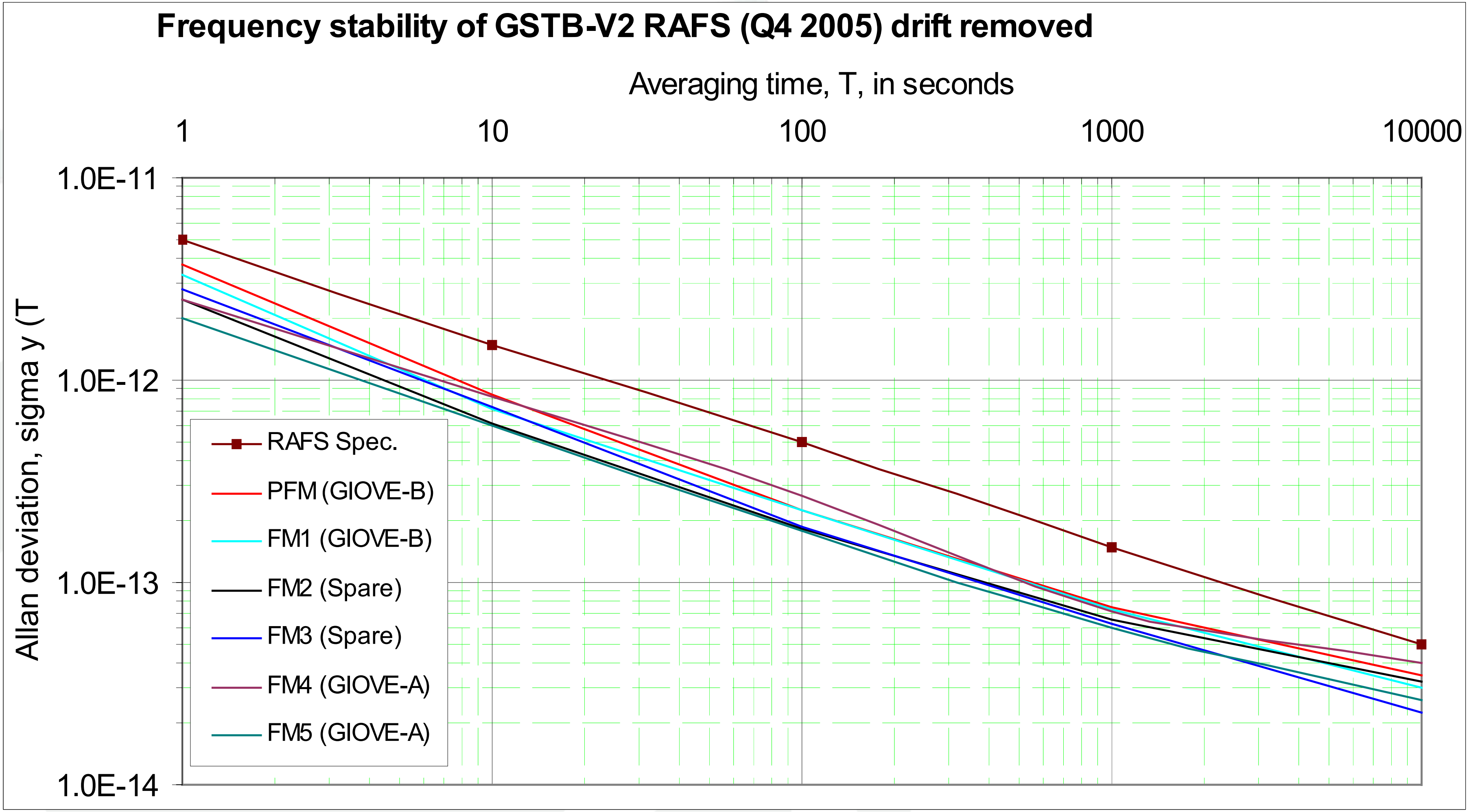


Drift removed: 2E-13 / day

Temperature: +-1°C



GSTB-V2 RAFS2 Measurement Results



RAFS2 for GSTB-V2 Performance Achieved

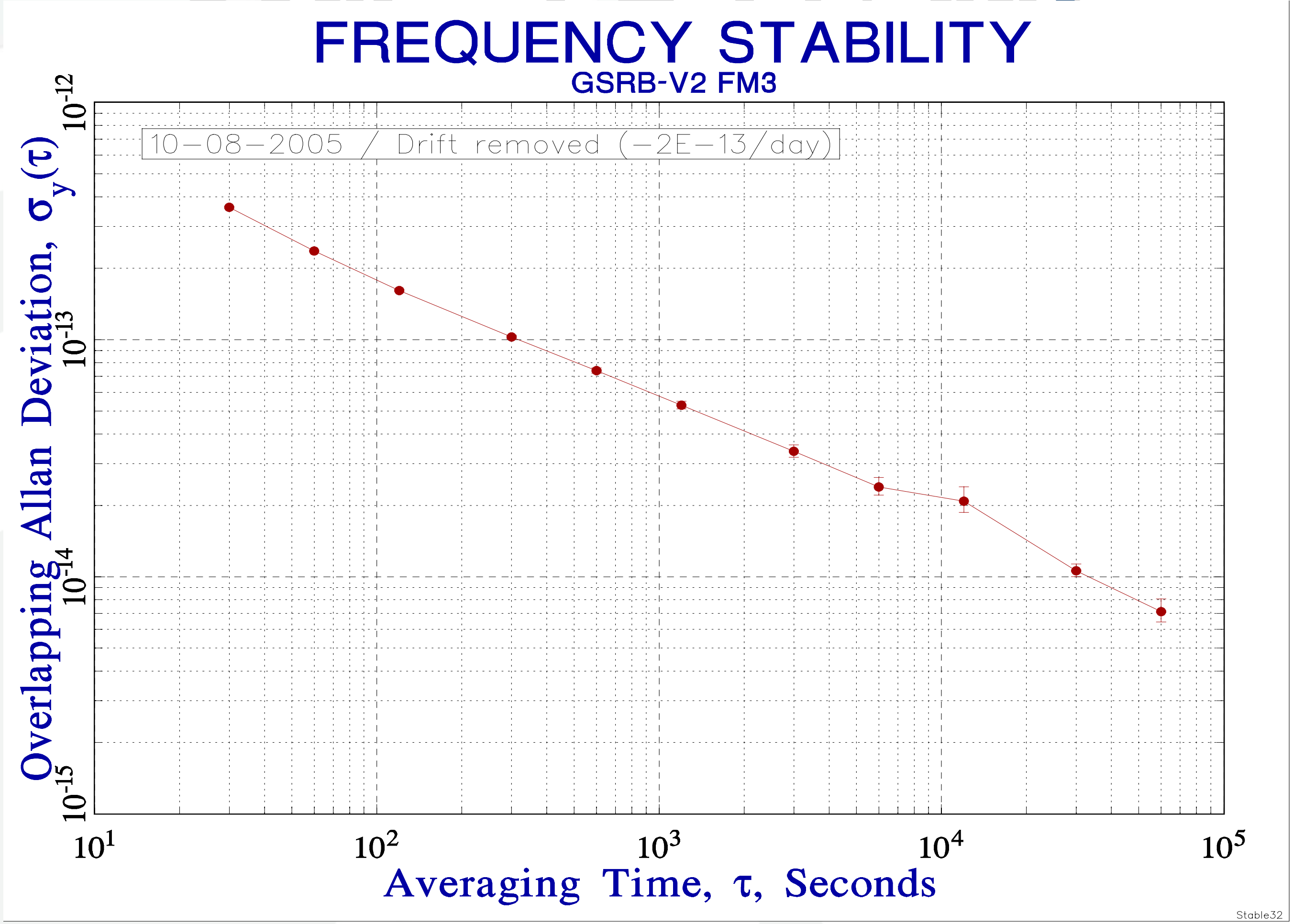
- ✓ **Frequency stability: $< 4x10^{-14}$ @ 10'000 sec**
- ✓ **Flicker floor : $< 3x10^{-14}$(drift removed)**
- ✓ **Thermal sensitivity: $< 5x10^{-14}$ /°C**
- ✓ **Magnetic sensitivity: $< 1x10^{-13}$ / Gauss**
- ✓ **Mass and volume: 3.2 kg and 2.4 lt**

GIOVE-A Preliminary information (FM4 and FM5)

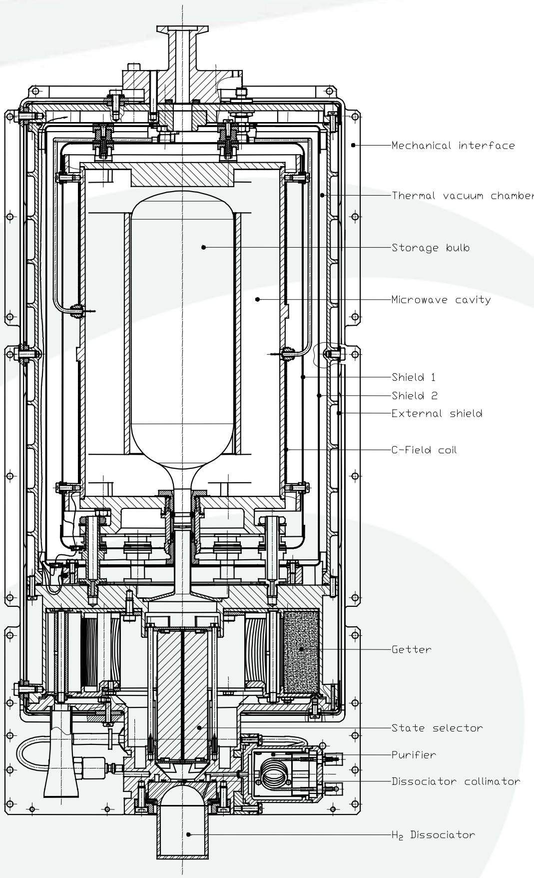
Start:	**Several start sequences all 100% nominal**
Rb Light TM:	**Nominal values and perfectly stable**
Rb Signal TM:	**Nominal values and perfectly stable**
Operating Temp.:	**Nominal**
Power:	**Nominal**

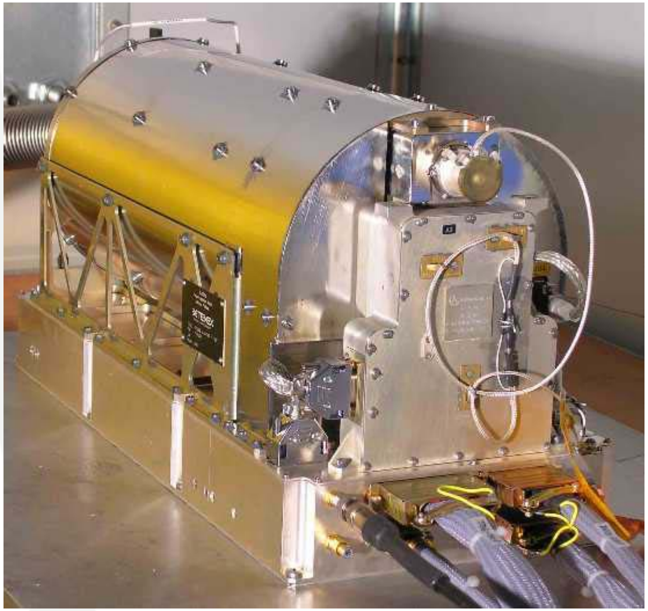
Ground segment measurements showing almost same stabilities values than on ground .

RAFS3 further improvements
Goal < 1 E-14 / day



Passive Hydrogen Maser for Galileo

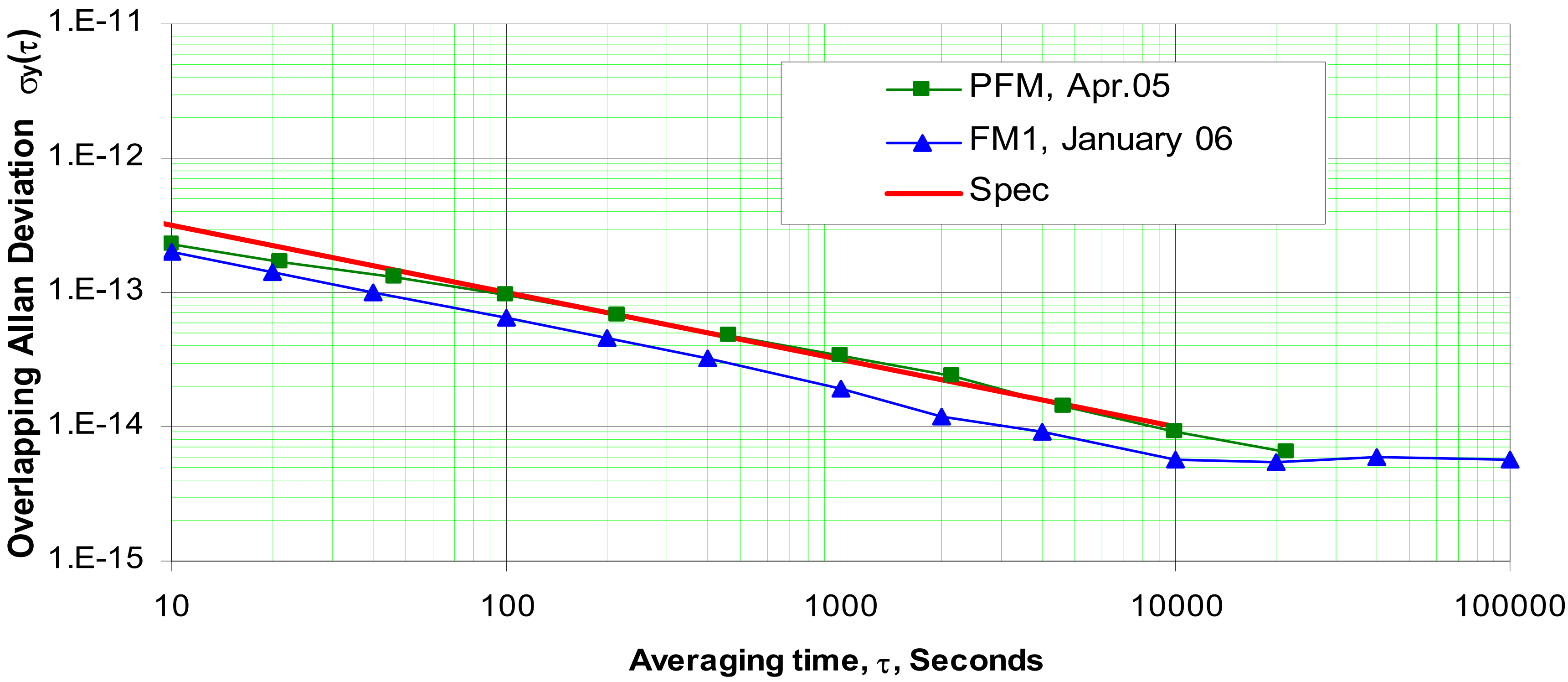




Complete clock delivered for Giove B sat

Galileo Avionica

PHM/FM Performance Improvement



Significant improvements obtained between PFM and FM models by improving cavity quality factor

Drift: <5E-15/day

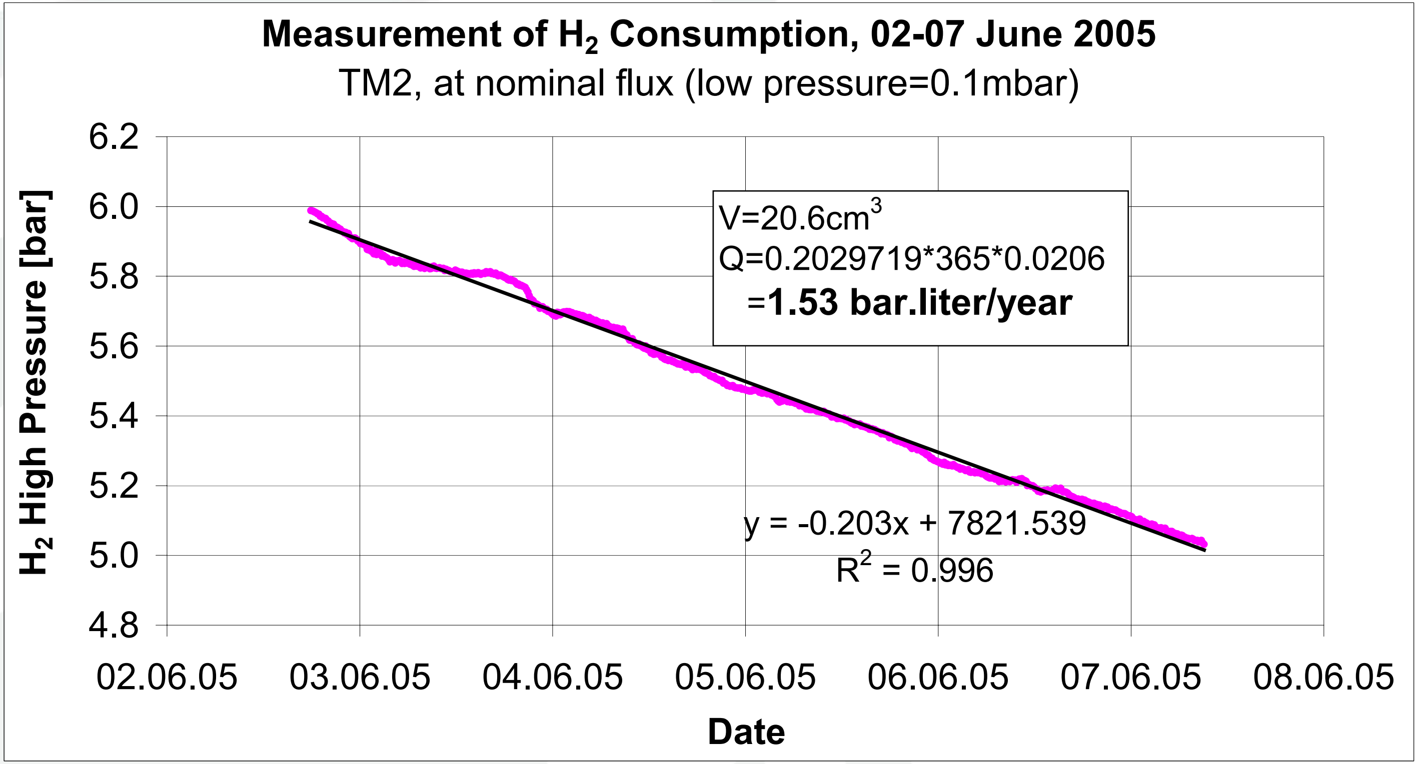
PHM for GSTB-V2 Performance Achieved

- ✓ **Frequency stability:** < $7 \times 10^{-13} \times t^{-1/2}$
  ($1s < t < 10'000s$)
- ✓ **Flicker floor :** < 6×10^{-15}
- ✓ **Drift:** < 5×10^{-15}/ day
- ✓ **Thermal sensitivity:** < 3×10^{-14}/°C
- ✓ **Magnetic sensitivity:** < 4×10^{-14}/Gauss
- ✓ **Mass and volume:** 18 kg and 28 lt

PHM Life Time

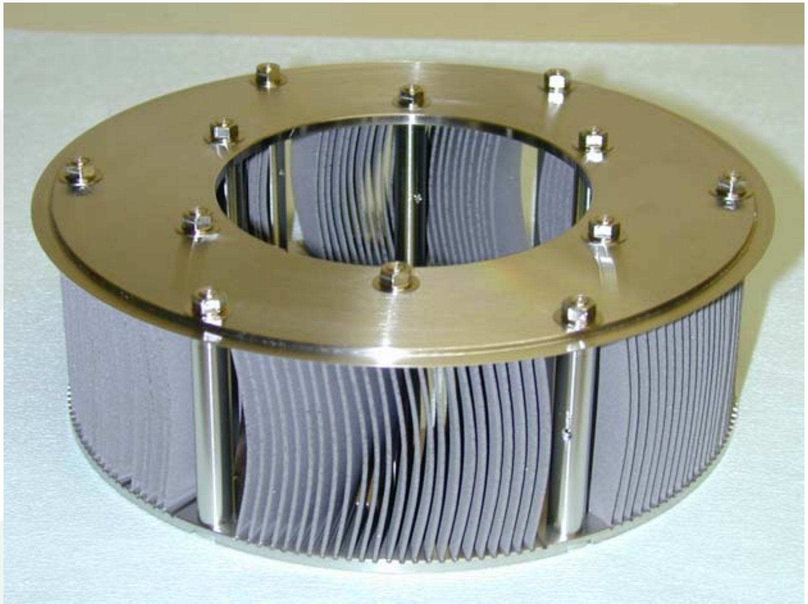
- 12 years orbit life + 1 year ground storage
  - The orbit life is limited by
    - Size of hydrogen container
    - Bulk getters mass (hydrogen sorption capacity)
    - Ion pump sorption capacity (for background gases)
    - Total dose of ionising radiation

H_2 Consumption test



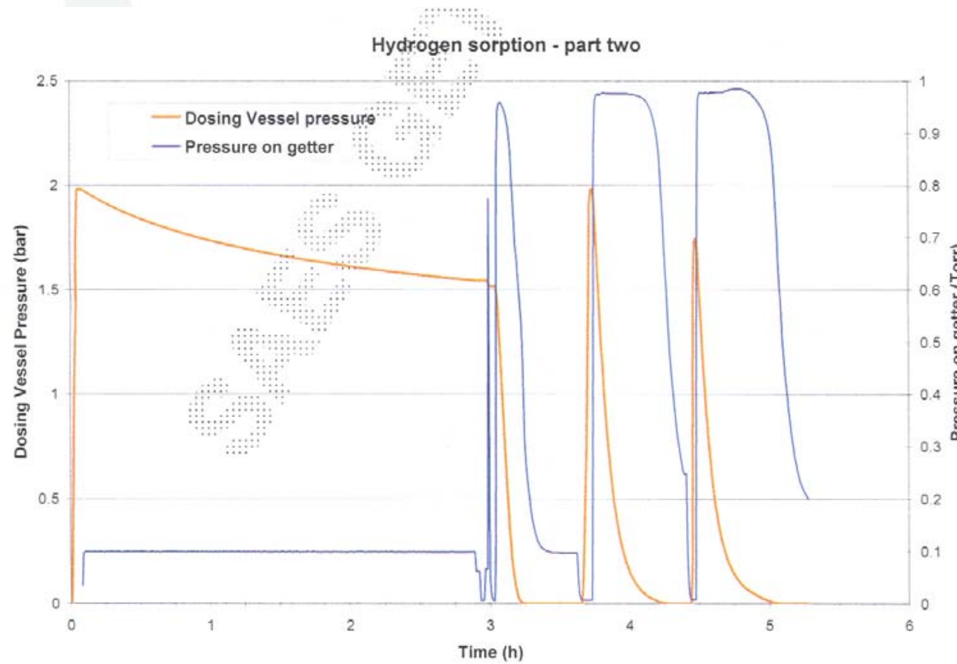
- H_2 container with the capacity of 25 bar.l is sufficient for 12-years life time, taking account of the margin.

PHM getters & high vacuum chamber



H_2 Sorption Test on Getter Cartridge

- Capable of sorbing the required amount of H_2 of 20 bar*l.
- Base pressure after sorption was in the low e-7 mbar range with only the getter cartridge pumping.



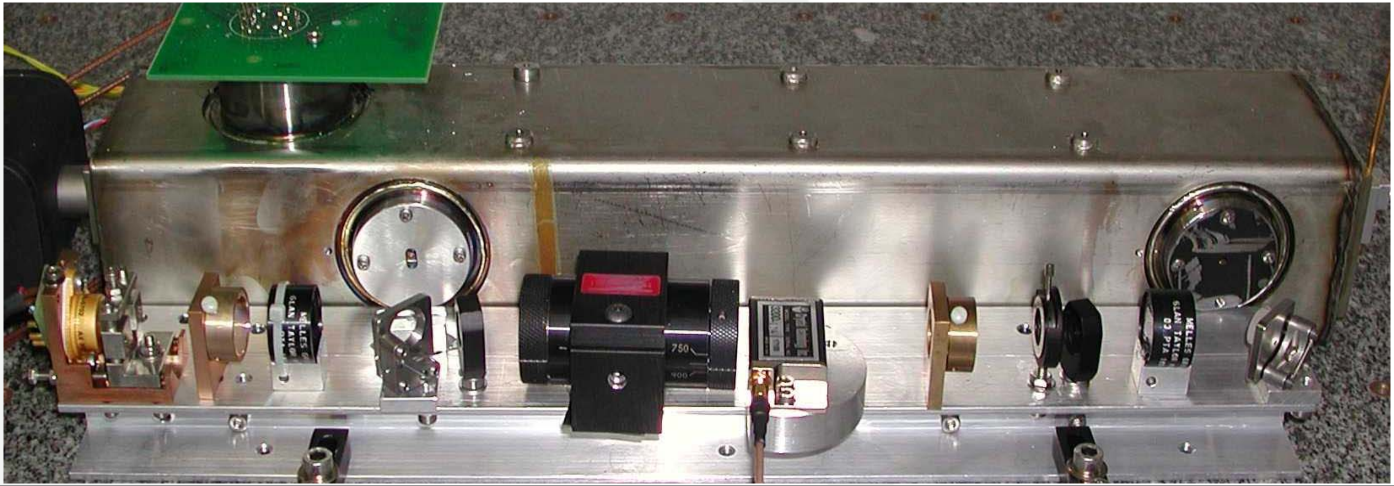
Sep. '03 at SAES Getter S.p.A

PHM for GSTB-V2 Qualification Status

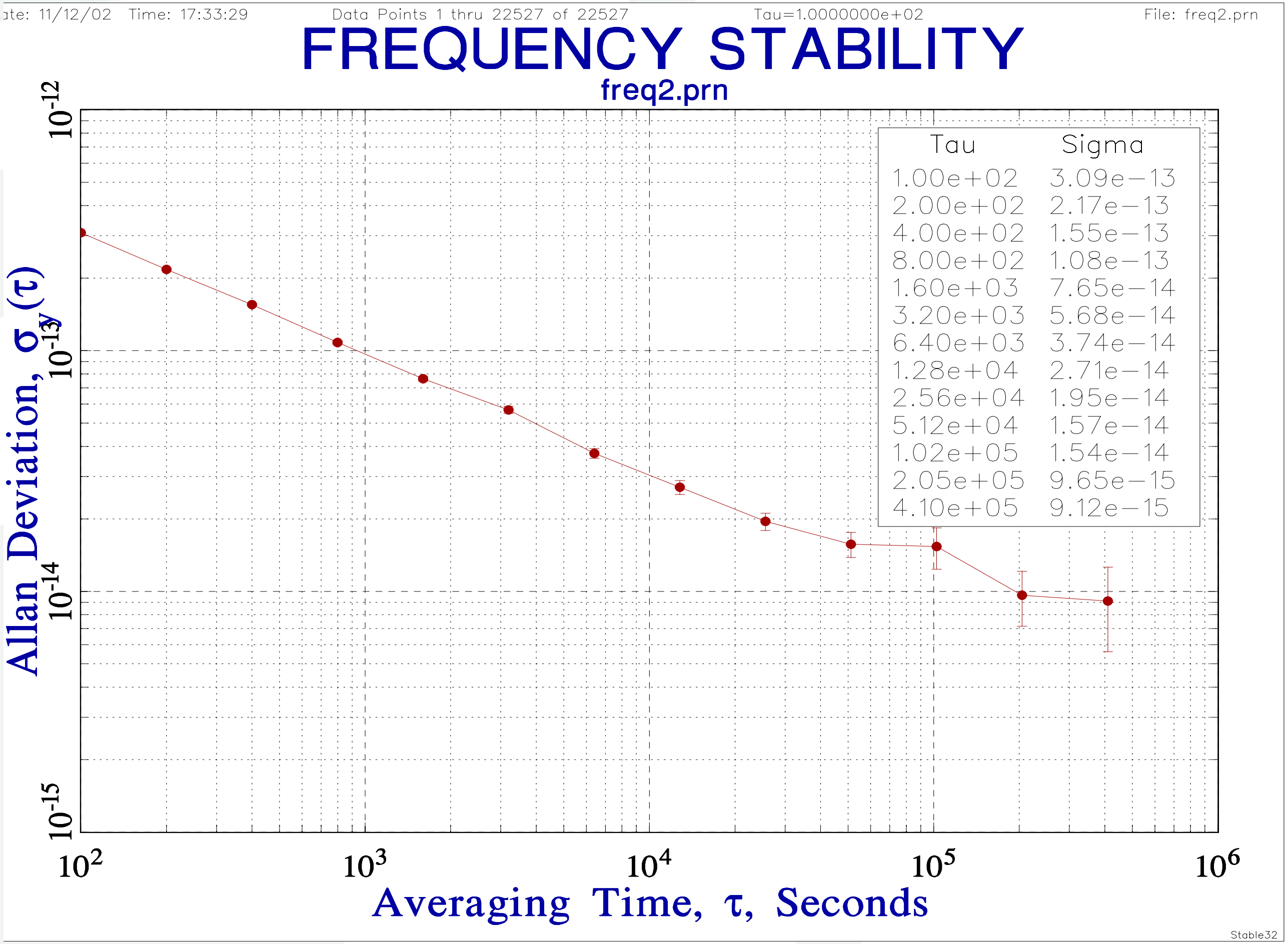
- ✓ **Vibration: Ok**
- ✓ **Shock: Ok**
- ✓ **EMC/EMI: Ok**
- ✓ **Thermal Vacuum: Ok**

Opticaly Pumped Cesium: BB (TEK SYS / 2002)

- The compact optically pumped cesium beam clock developed by Tekelec Systemes with the scientific support of the SYRTE exhibits a frequency stability of $3.10^{-12}\tau^{-1/2}$ measured against a hydrogen maser as a reference in 2002.
- The sealed tube works under a low atomic flux consistent with lifetime of 8 years or more. It uses a 22 cm long Ramsey cavity
- The compact 3 cm wide optical bench is rigidly fixed along the tube which length is 45 cm.

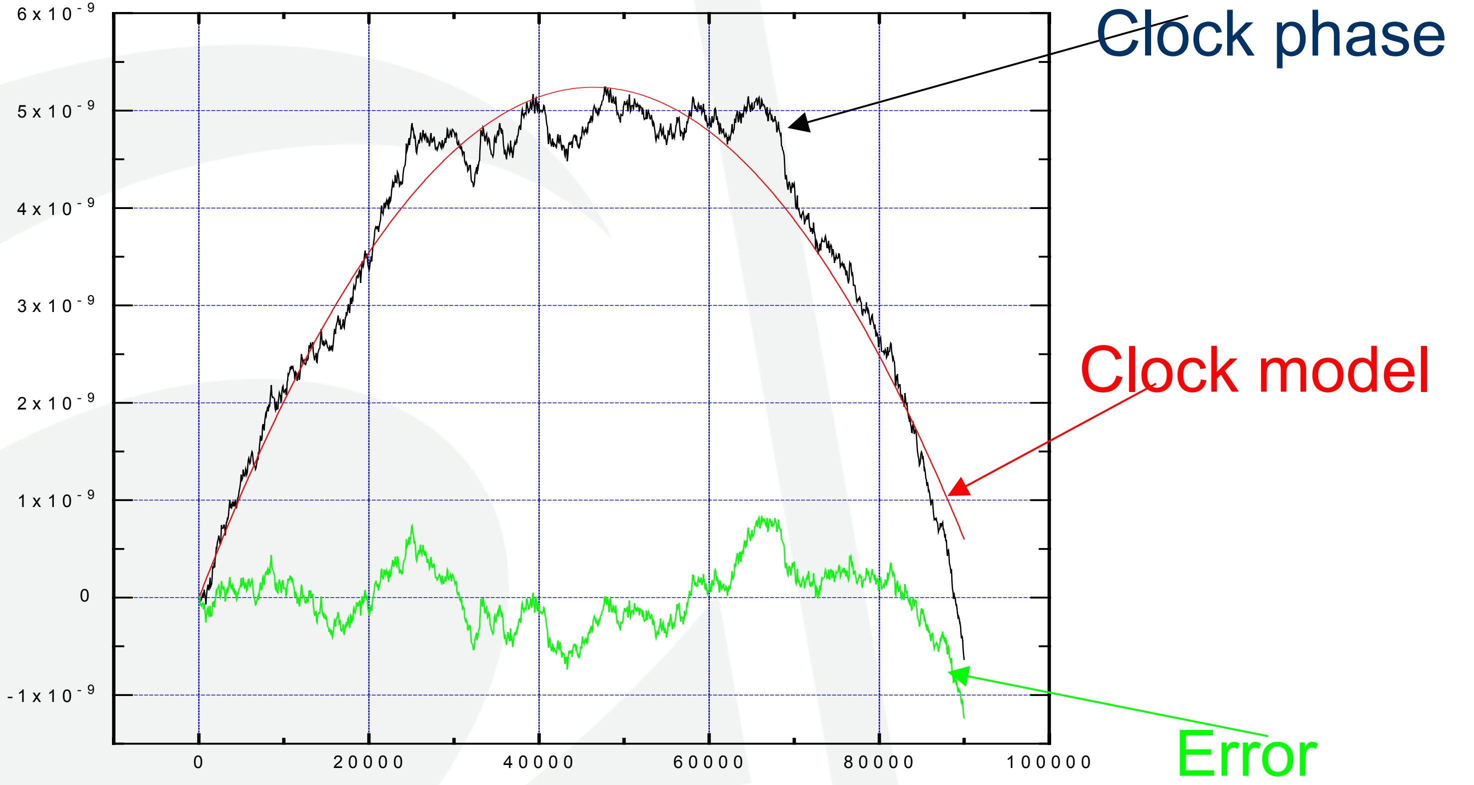


OPCs :BB Stability (TEK SYS/ dec 2002)

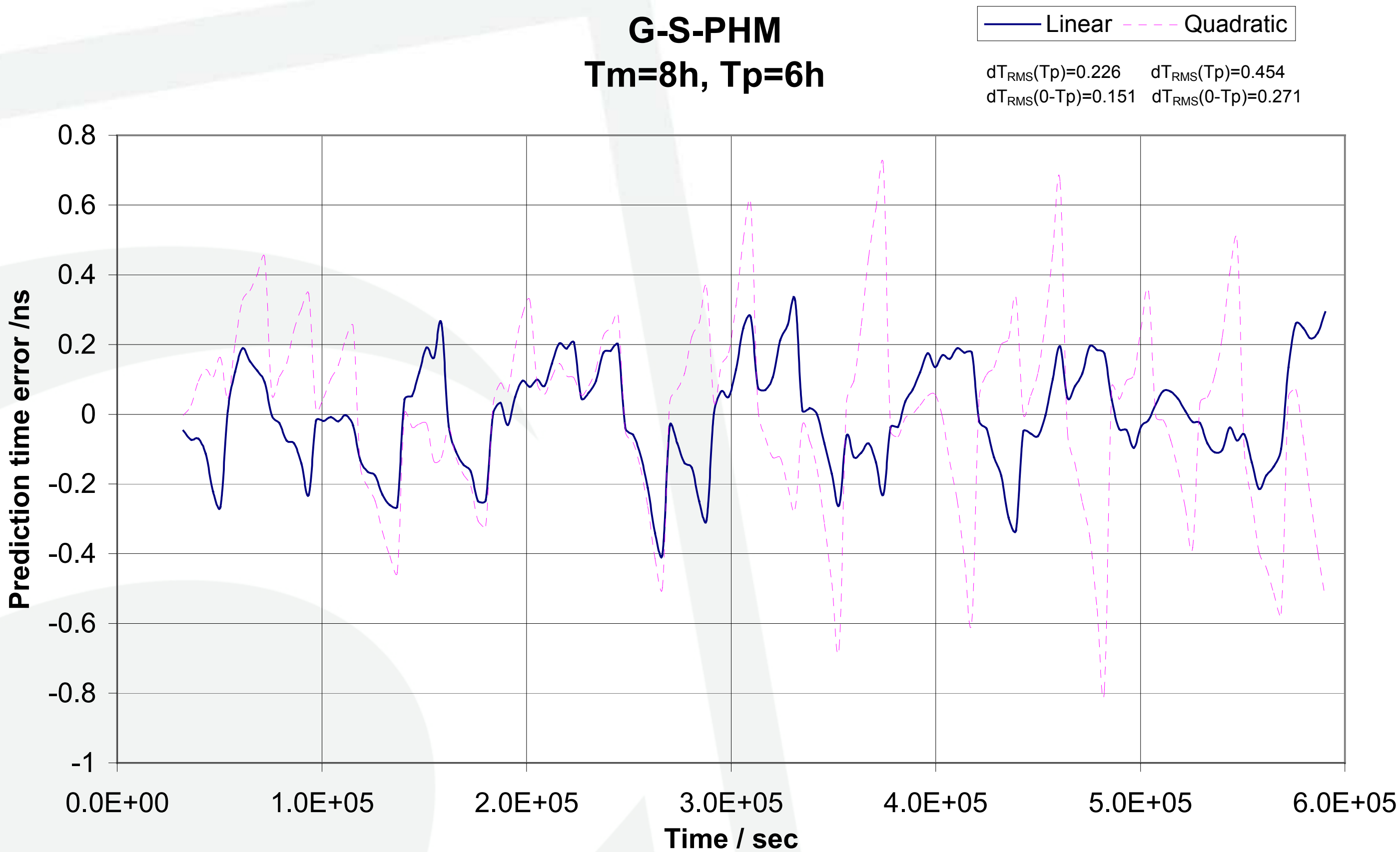


Clock model & prediction time error:

predictive system : error will be the difference between the clock phase-time & the establish clock model from previews collected data.



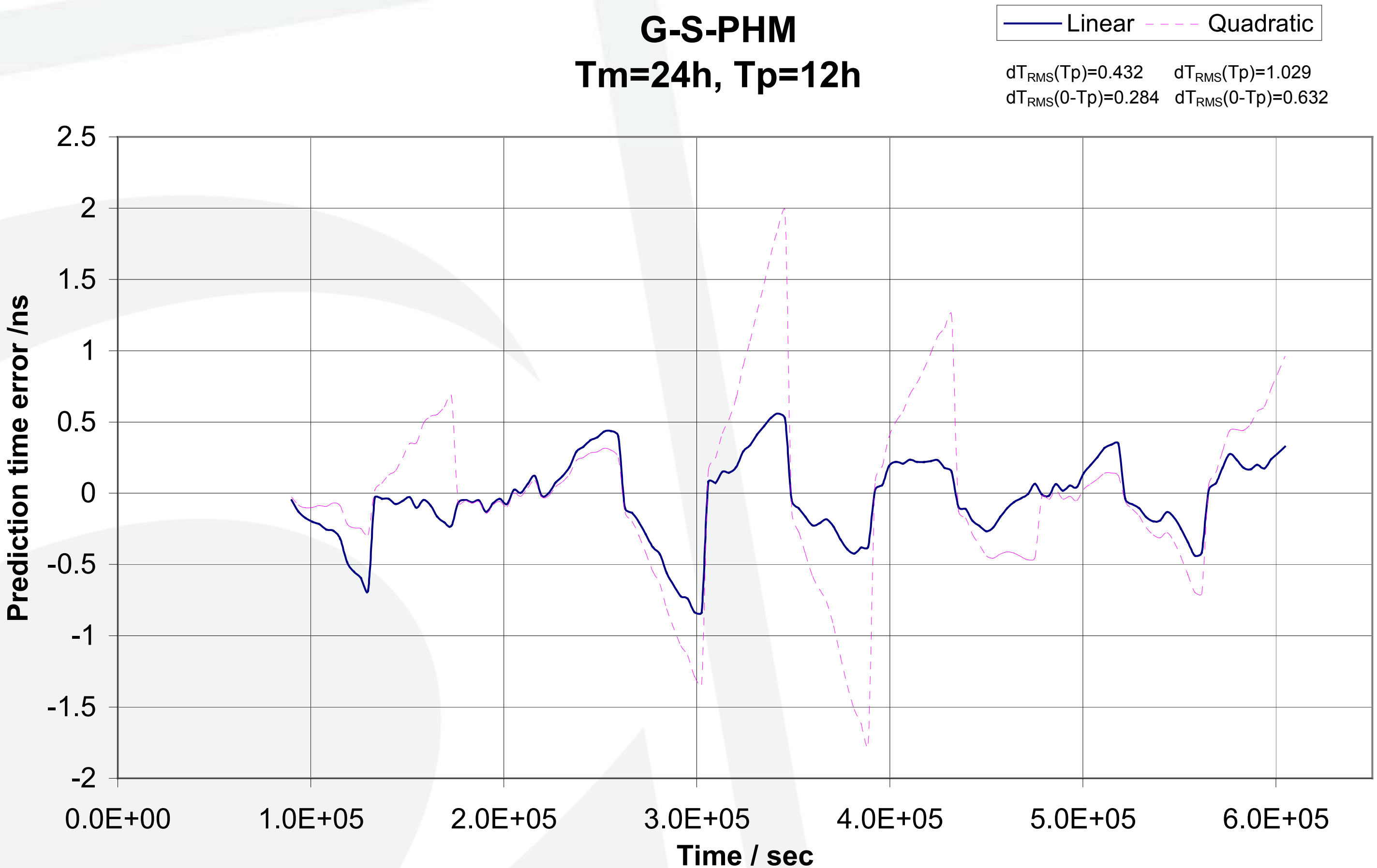
Prediction Time error for S_PHM:



Tm = Measurement Time Method: Curve fitting during Tm

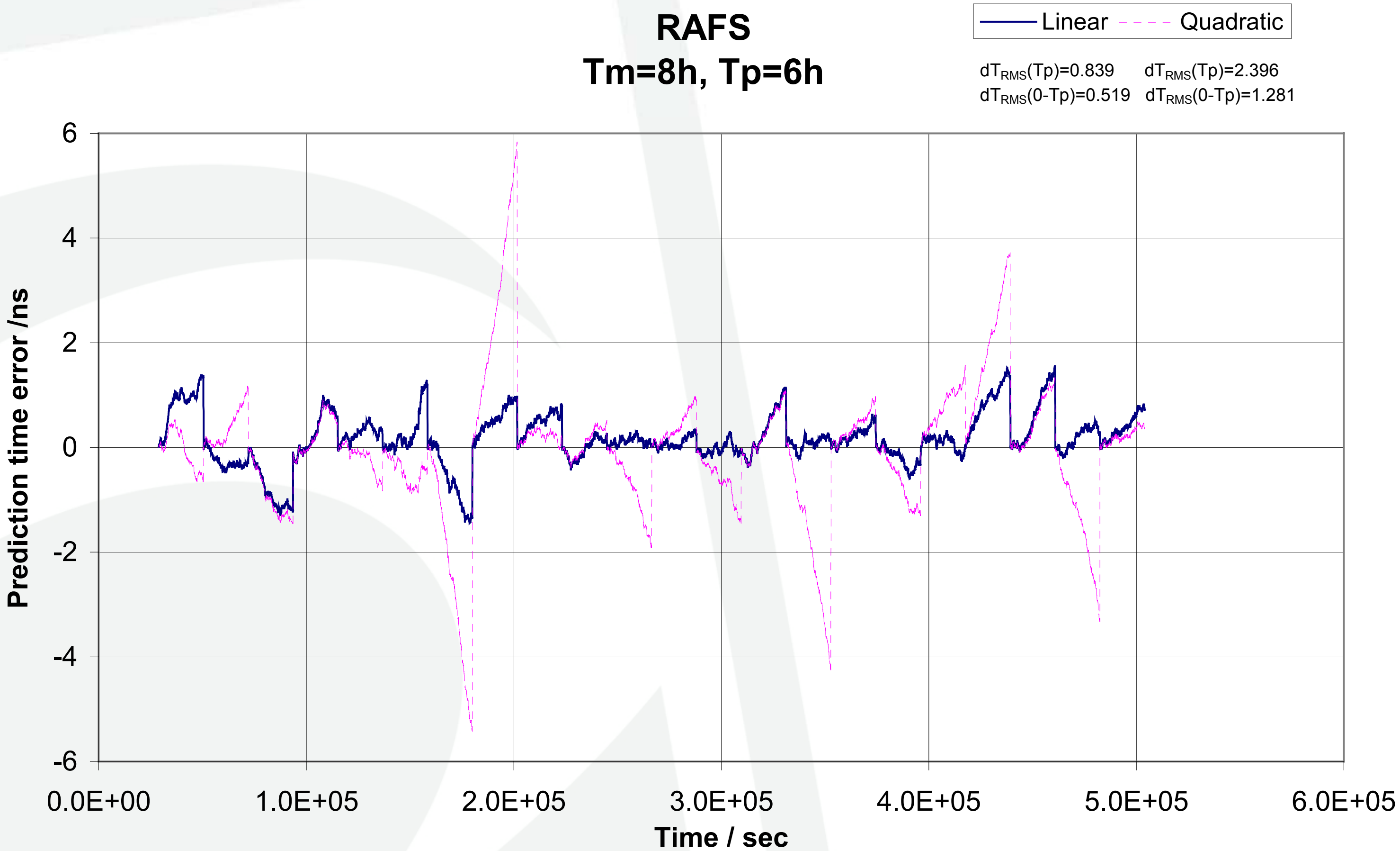
Computed by Q. Wang Tp = Prediction Time Plot: Diff. Between fit and meas. da

Prediction Time error for S_PHM:



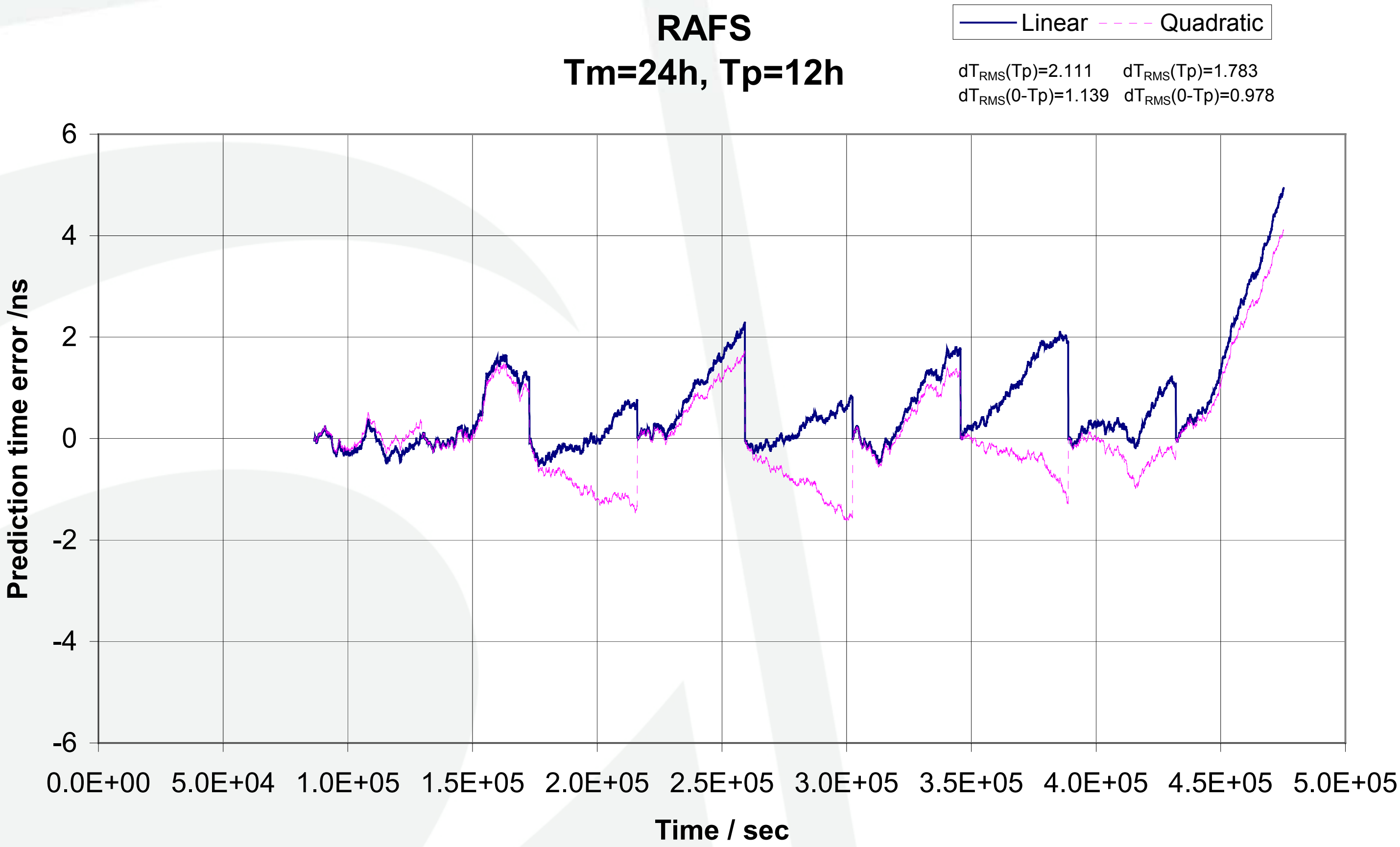
Computed by Q. Wang

Prediction Time error for RAFS:



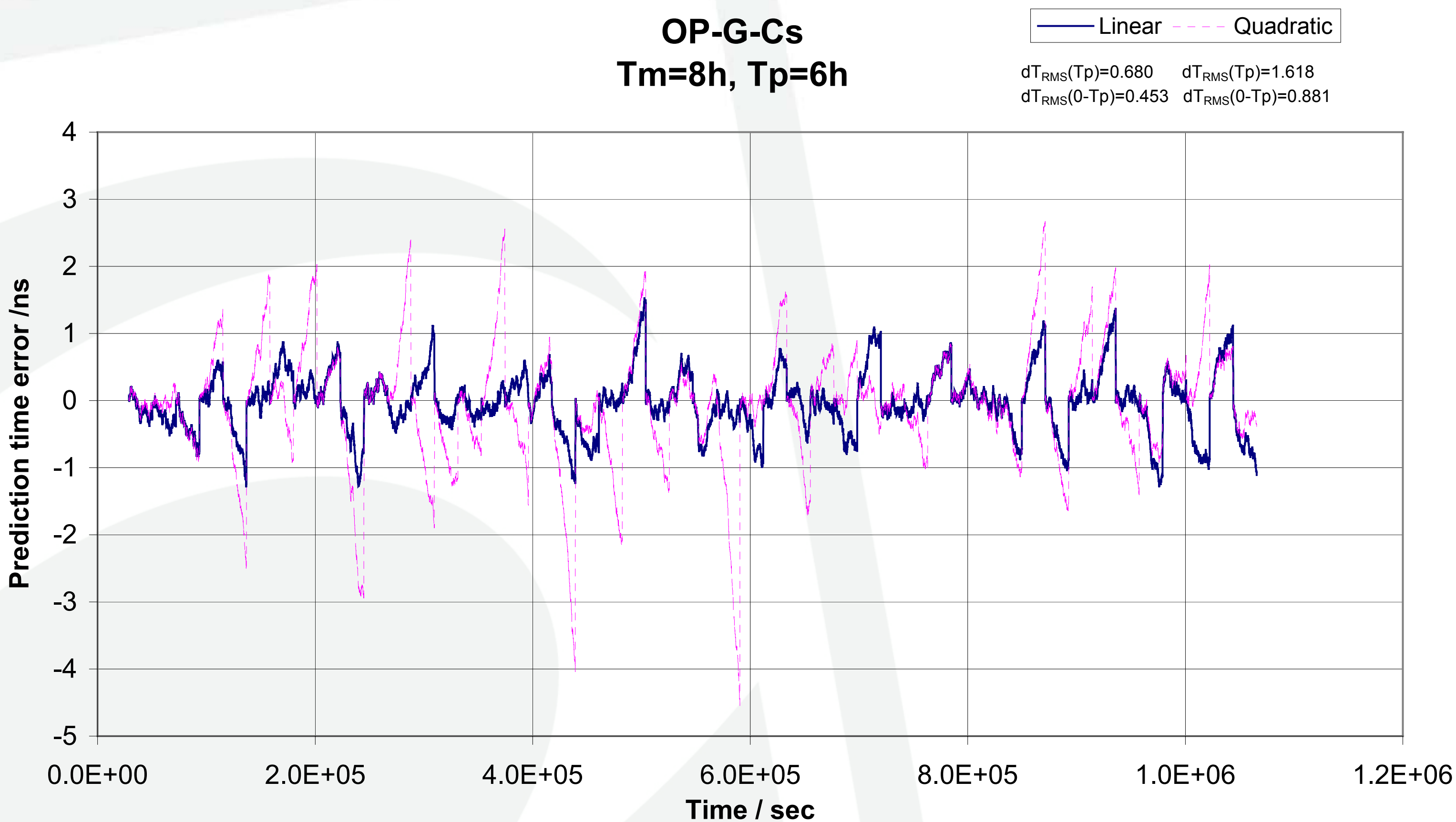
Computed by : Q. Wang

Prediction Time error for RAFS



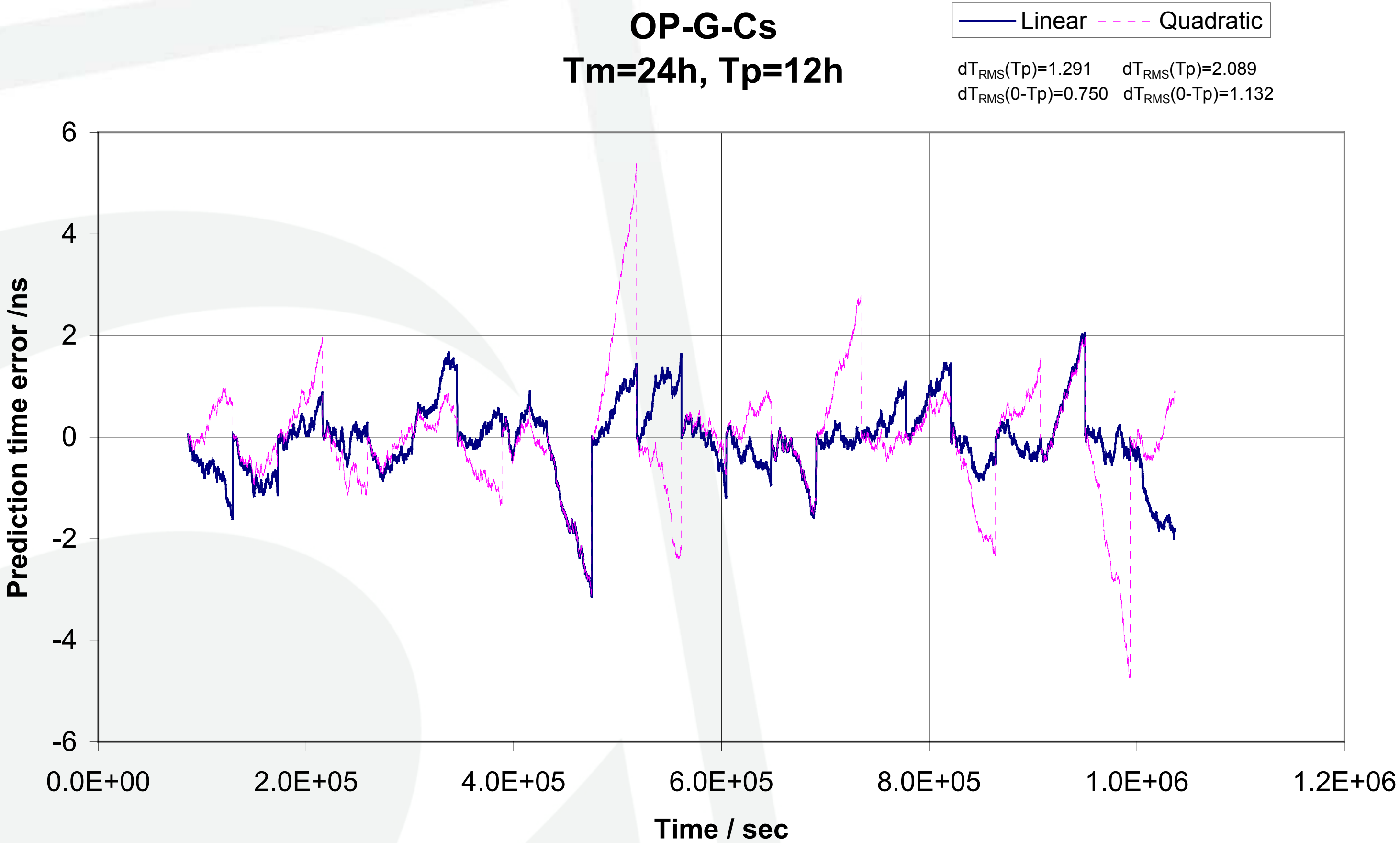
Computed by : Q. Wang

Prediction Time error for OPCs



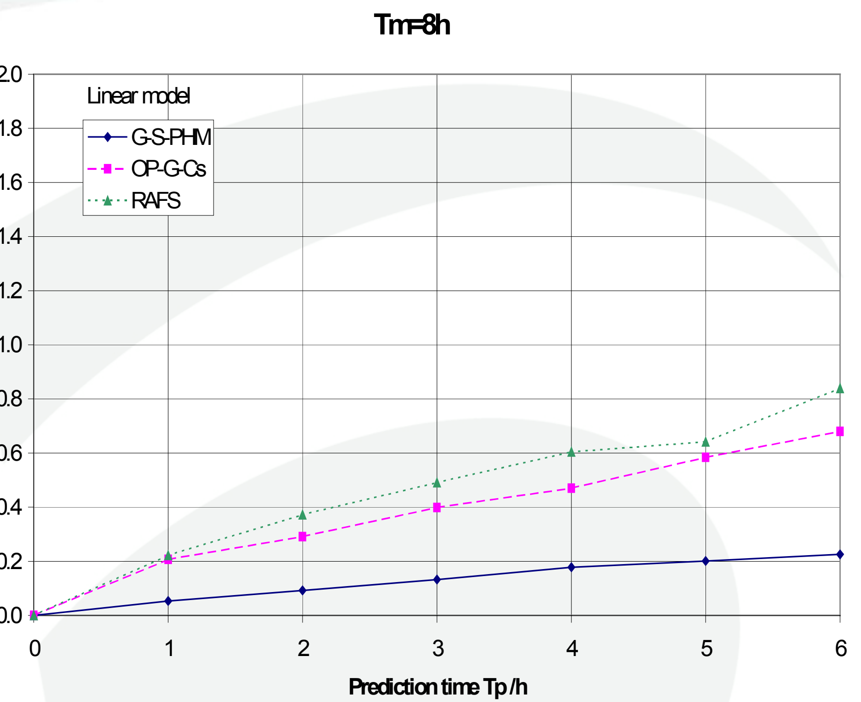
ata collected by TEKELEC SYSTEME on OPCs BB model

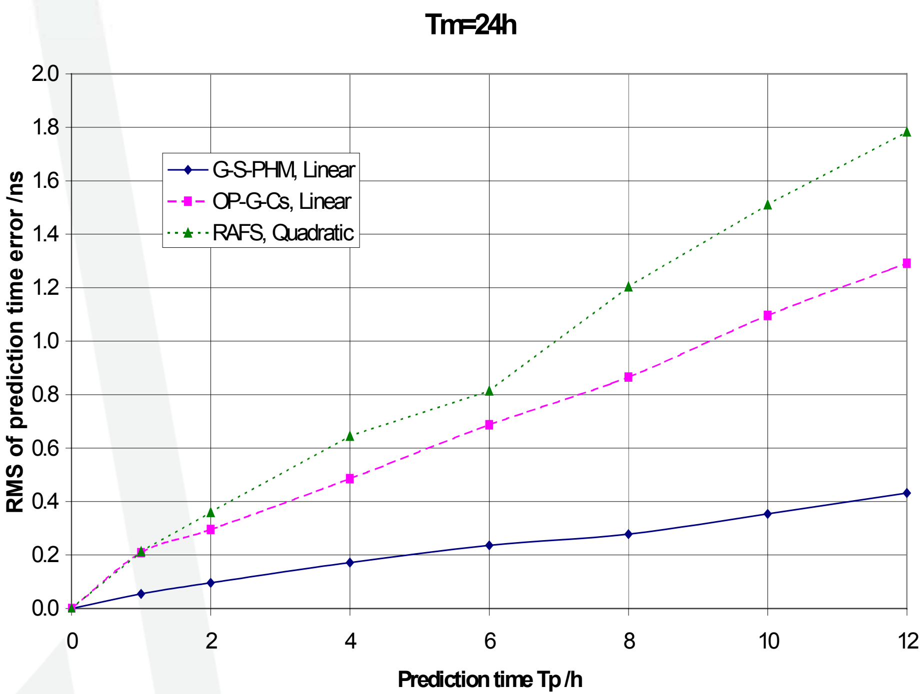
Prediction Time error for OPCs



Data collected by TEKELEC SYSTEME on OPCs BB

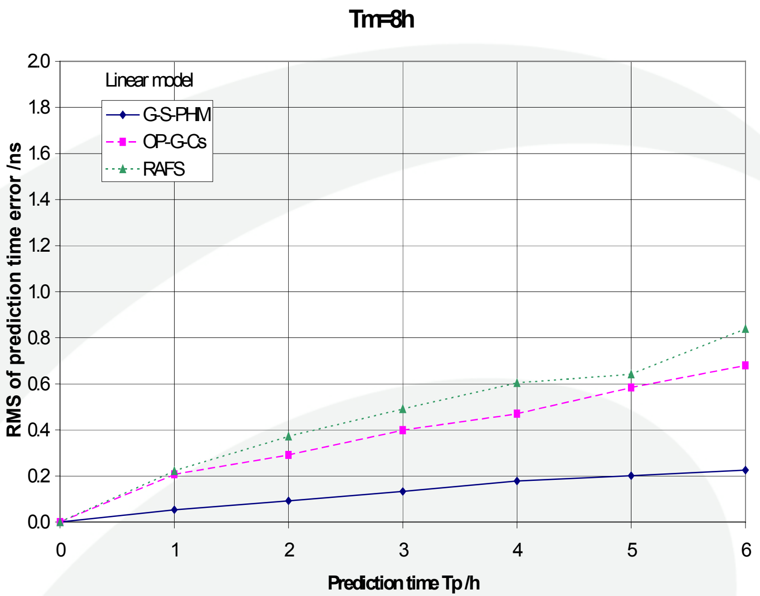
RMS of Prediction Time Error:

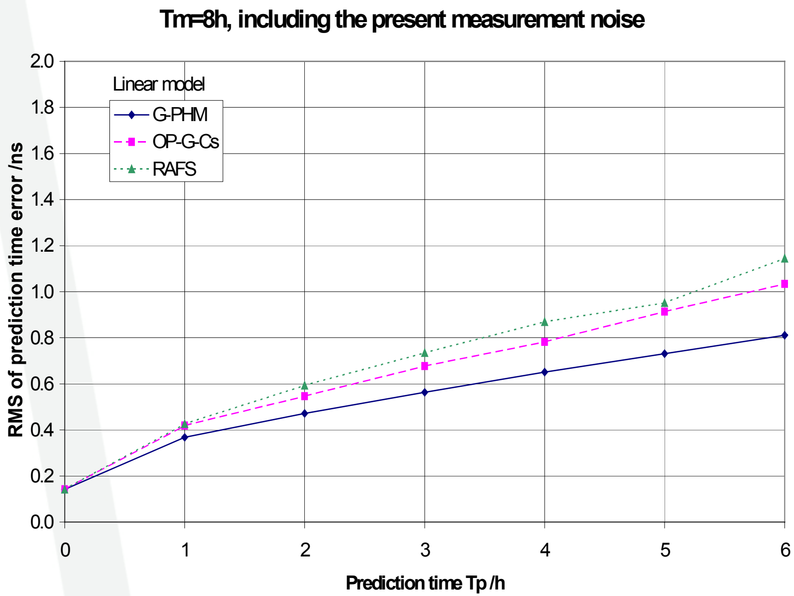




Method : RMS calculation of all error values after Tp

RMS of Prediction Time Error Tm=8h





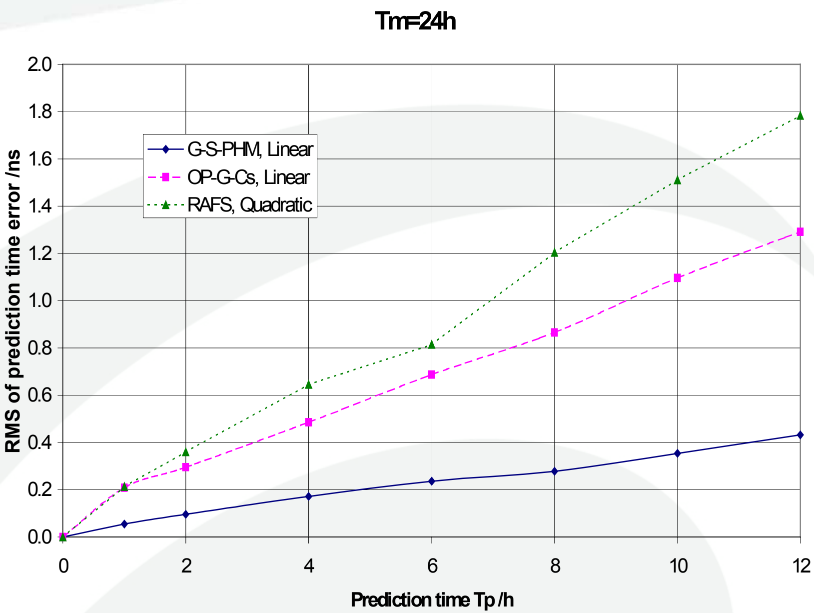
Without geodetic measurement noise

With present geodetic measurement noise

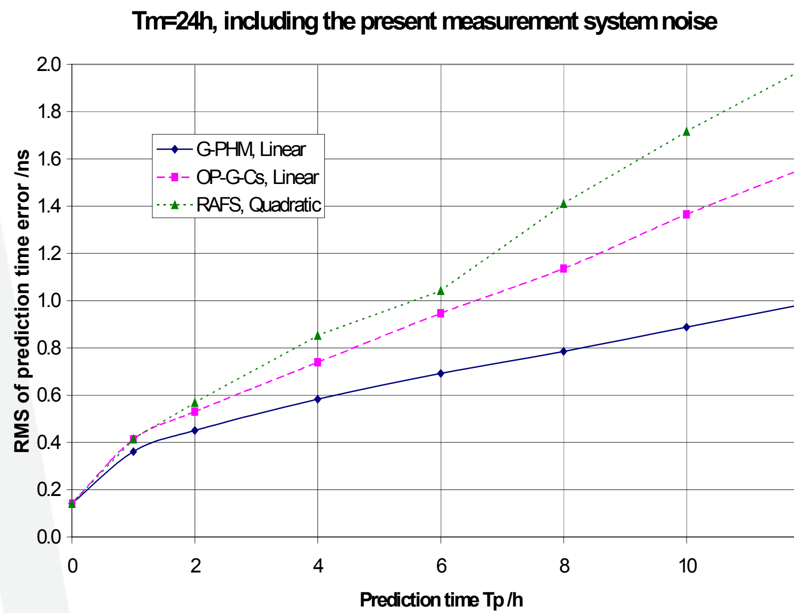
Method : RMS calculation of all error values after Tp

Computed by : Q. Wang / G. Busca

RMS of Prediction Time Error Tm=24h



Without geodetic measurement noise



With present geodetic measurement nois

Method : RMS calculation of all error values after Tp

TEMEX

Conclusions:

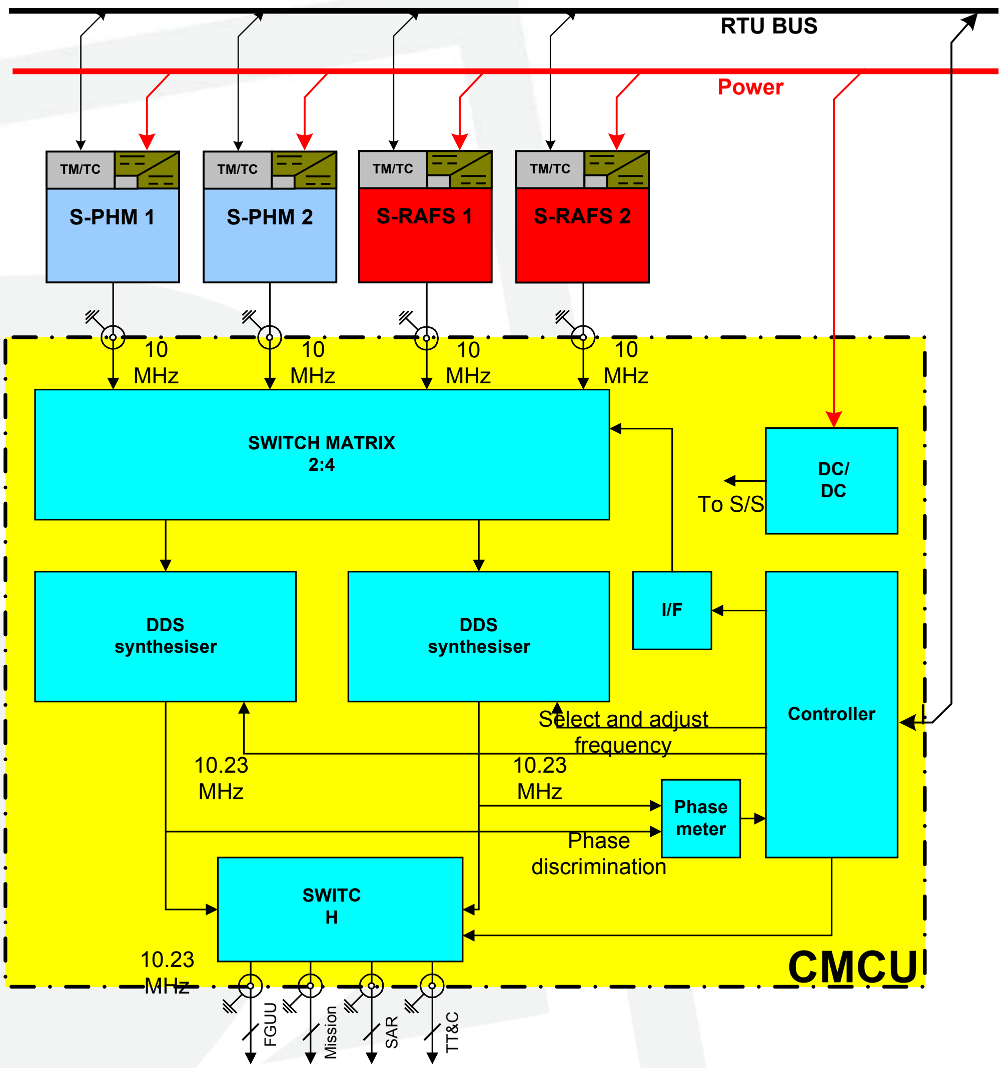
With the present S_Clocks measurement system noise, and prediction time up to 6 hours , the S_RAFS is adequate.

For future measurement system noise which are expected to improve by factor of 3 , the S_PHM will be the more adequate clock for prediction time up to 24 hours.

Navigation accuracy less than 1 m can be achieved with up to hours autonomy with RAFS and up to several days with passive Maser

Cesium clock degrading accuracy while not improving autonomy

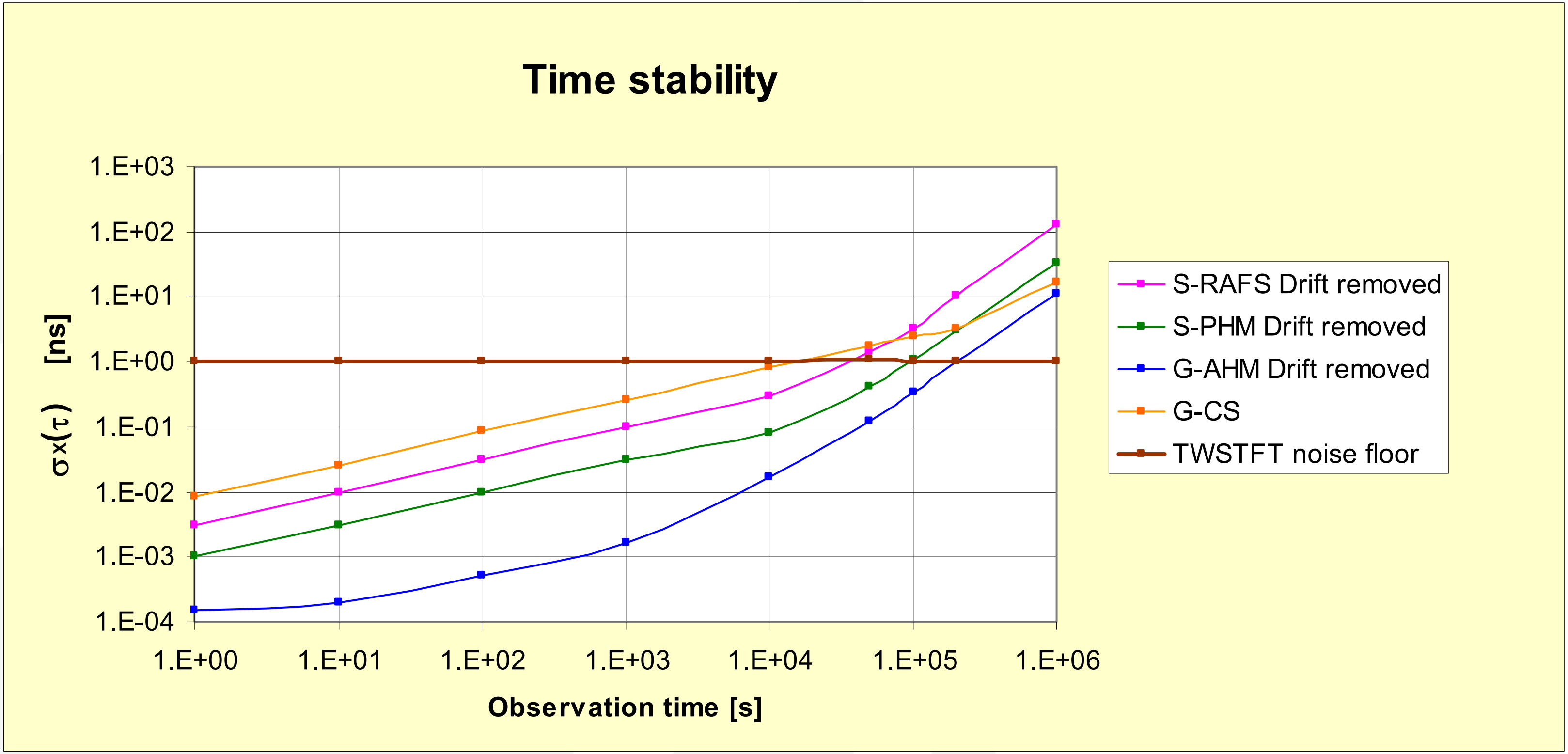
Galileo On-Board Clocks ensemble



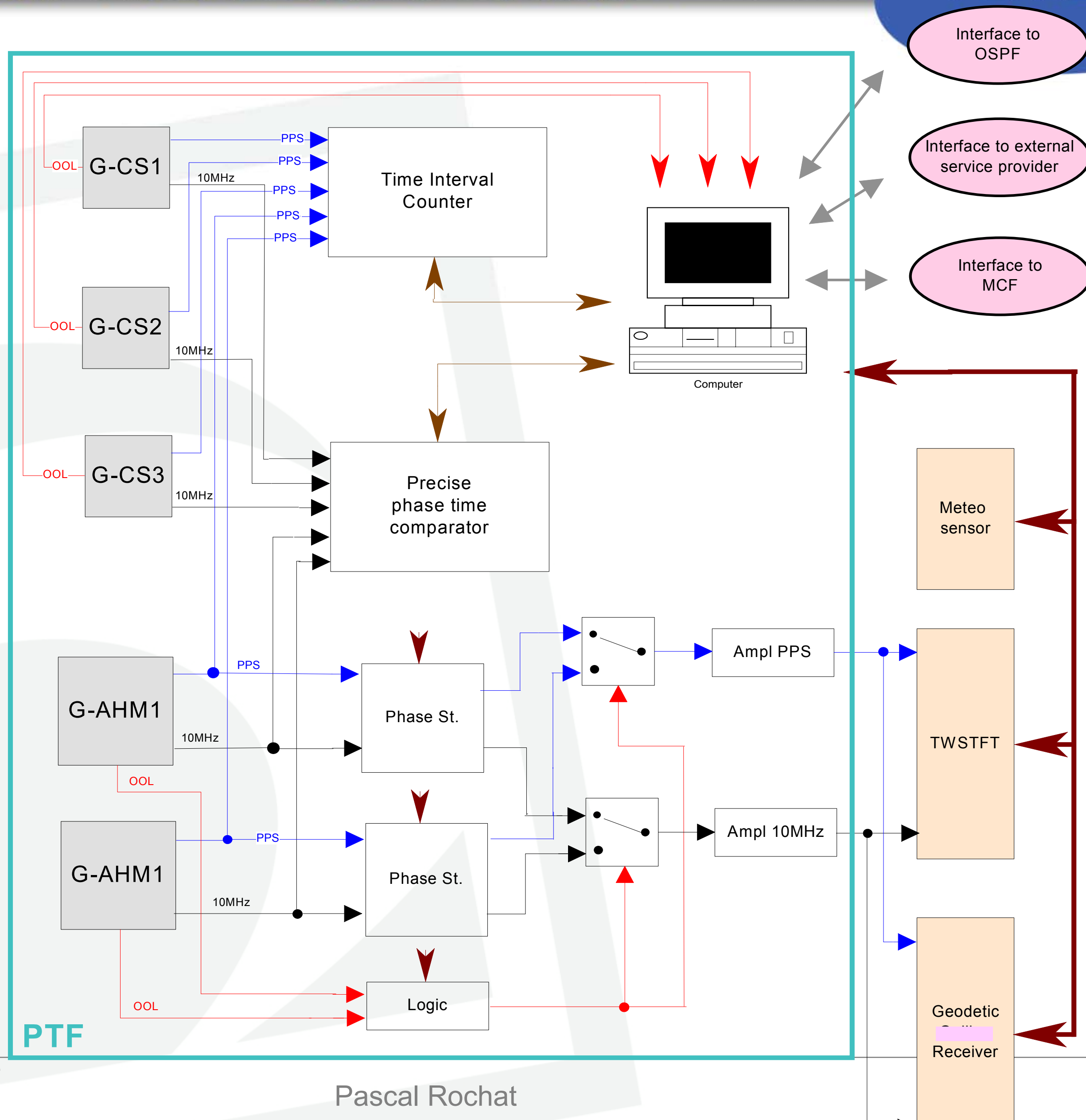
Navigation System Time reference generation (ground segment) shall meet following requirements

- Be linked to UTC time or other navigation system (s) for inter-operability purposes
- Be equipped with booth long term & short term stability clocks
- Autonomous switching of redundant master clocks
- Be linked to system by physical generation of time signal to at least one geodetic ground observation station.
- System time shall be generated within 1 ns stability for weeks in order to guarantee proper on board clocks stabilities and set-up on board clocks modelling.

Space and Ground Clocks Time Stability



Exemple of System Time generation Architecture



Conclusions

Qualified clocks technologies Offering:

1. Metric / sub metric navigation accuracy
2. Up to one week autonomy capability with on board Maser technology
3. Cold + Hot Redondancy on board of each satellite
4. Clocks lifetime expectation of 14 years or more
5. Simple & Mature Technologies offering room for improvements in term of mass & performances
6. Existing groung maser clocks offering better stability than Cesium for inter-operable navigation system linked with precise time transfert equipments

Thank you very much for your attention

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