

МОСКВА, 2–3 октября 2024 года

# Рубидиевый генератор как источник 1PPS погрешностью менее 100 нс в сутки

Баранов Алексей Анатольевич, к. ф.- м. н.,  
директор по разработкам АО Морион, Санкт-Петербург

# Области применения

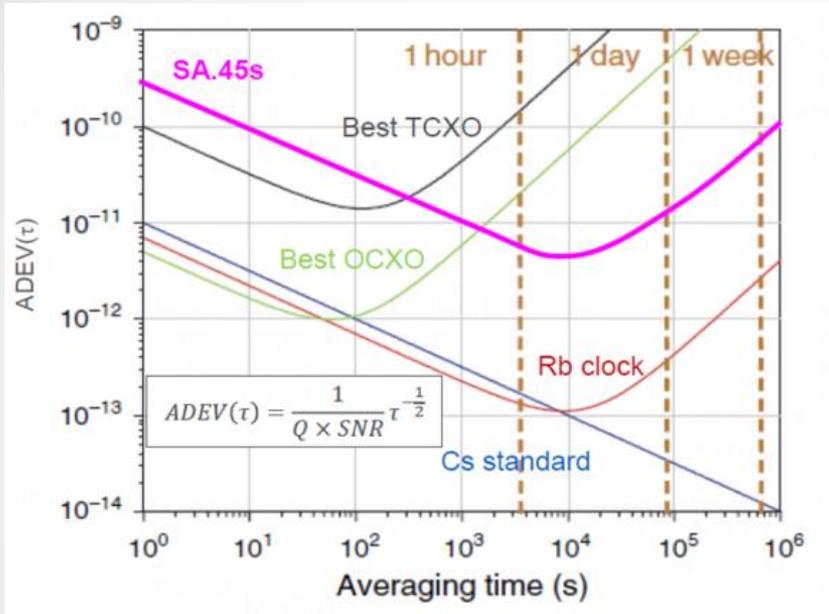
- Секунды/сутки ( $10^{-5}$ )  
ПК, наручные часы и пр.      Тактовые кварцевые генераторы  
MEMS генераторы

- Миллисекунды/сутки ( $10^{-8}$ )  
Лабораторные приборы  
10/100BASE Ethernet (Tx/Rx)      TCXO Термокомпенсированные КГ  
LC\*  
MEMS генераторы

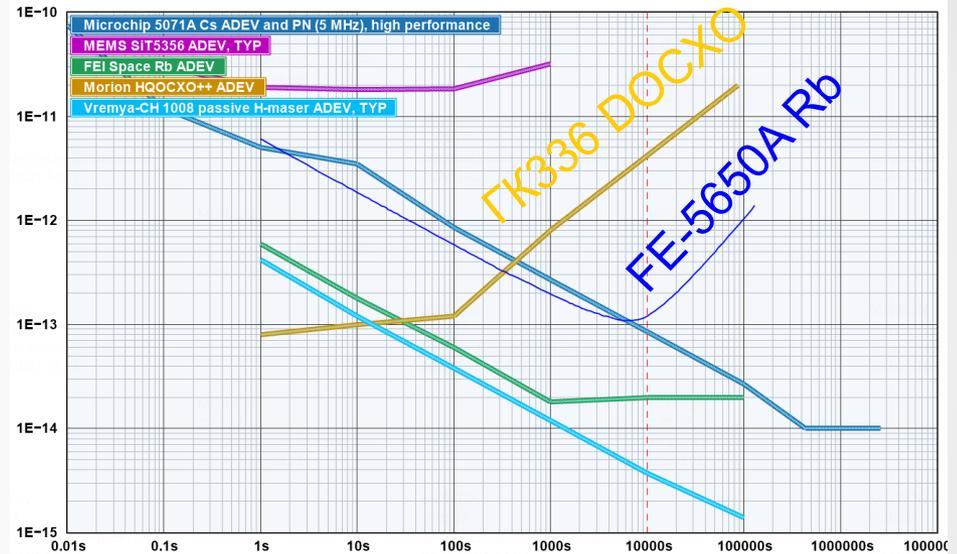
- Микросекунды/сутки ( $10^{-11}$ )  
Сетевая инфраструктура (телевещание, сотовая связь)  
Прием сообщений в т.ч. финансовых (синхронизация транзакций)  
Навигация (инерциальная, высокоточная спутниковая)      Rb  
Шифрование      HQOCXO (термостатированные КГ)

- Наносекунды/сутки ( $10^{-13}$ )  
Воспроизведение времени      Space Rb  
GNSS (бортовые атомные часы)      Cs  
Физические эксперименты      H

# Типовая девиация Аллана

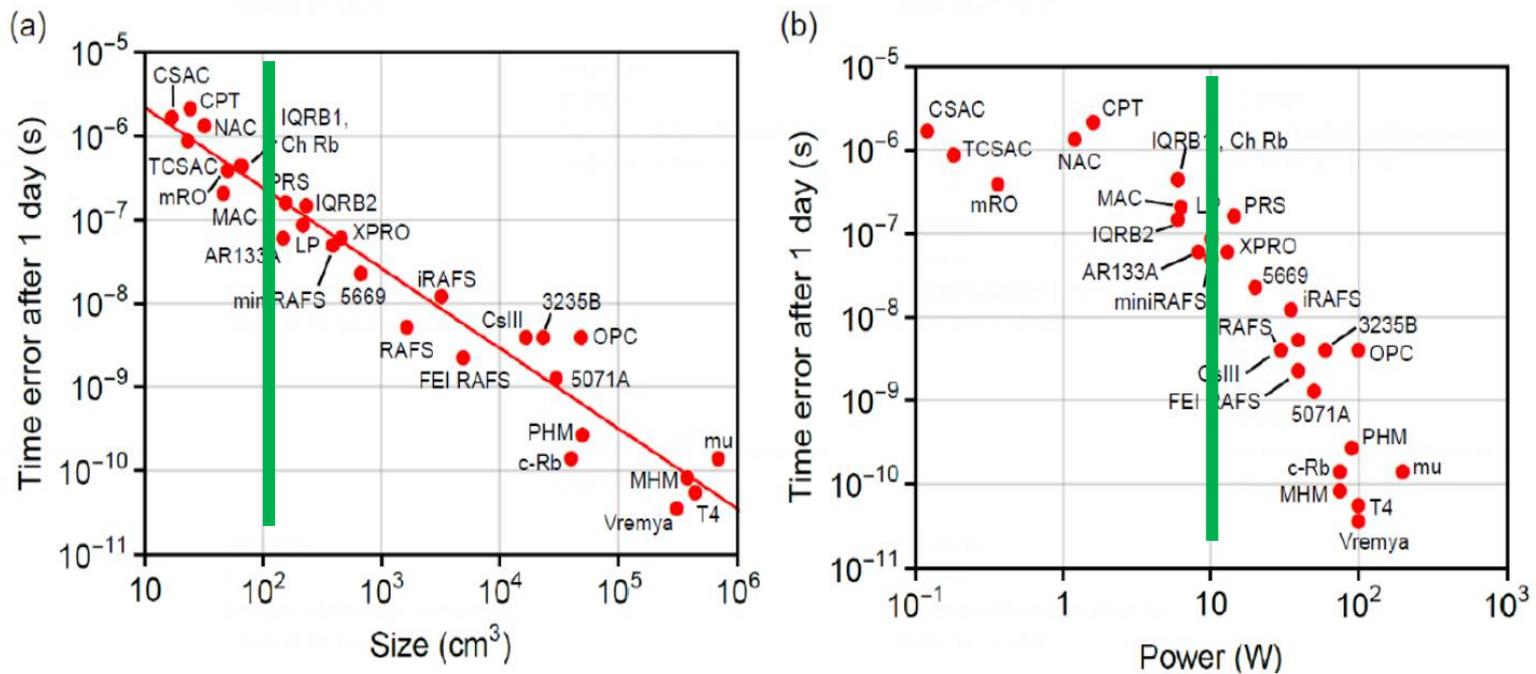


2009



2024

# Набег фазы за 1 сутки в зависимости от габаритов и энергопотребления источника



3. L. Schmittberger et al., "A Review of Commercial and Emerging Atomic Frequency Standards", IEEE TRANSACTIONS ON ULTRASONICS, FERROELECTRICS, AND FREQUENCY CONTROL, pre-published, 2021

# Характеристики рубидиевых генераторов



FS725



22x9x33=6500 cm<sup>3</sup>

HP 5065 A



PRS 10

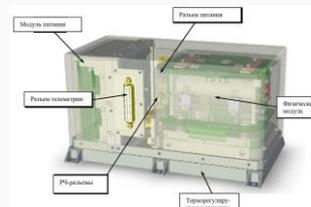


5x7.5x10=375cm<sup>3</sup>

FE 5680A



2.5x9x12=270cm<sup>3</sup>



22x12x12=3200 cm<sup>3</sup>

Double  $\mu$ w-optical resonance



Russia 5x5x2.5=63 cm<sup>3</sup>, 6W



UK, 75cm<sup>3</sup>, 6W

CPT



USA, 5x5x2=50cm<sup>3</sup>, 100g, 6W

Chengdu XHTF 1031

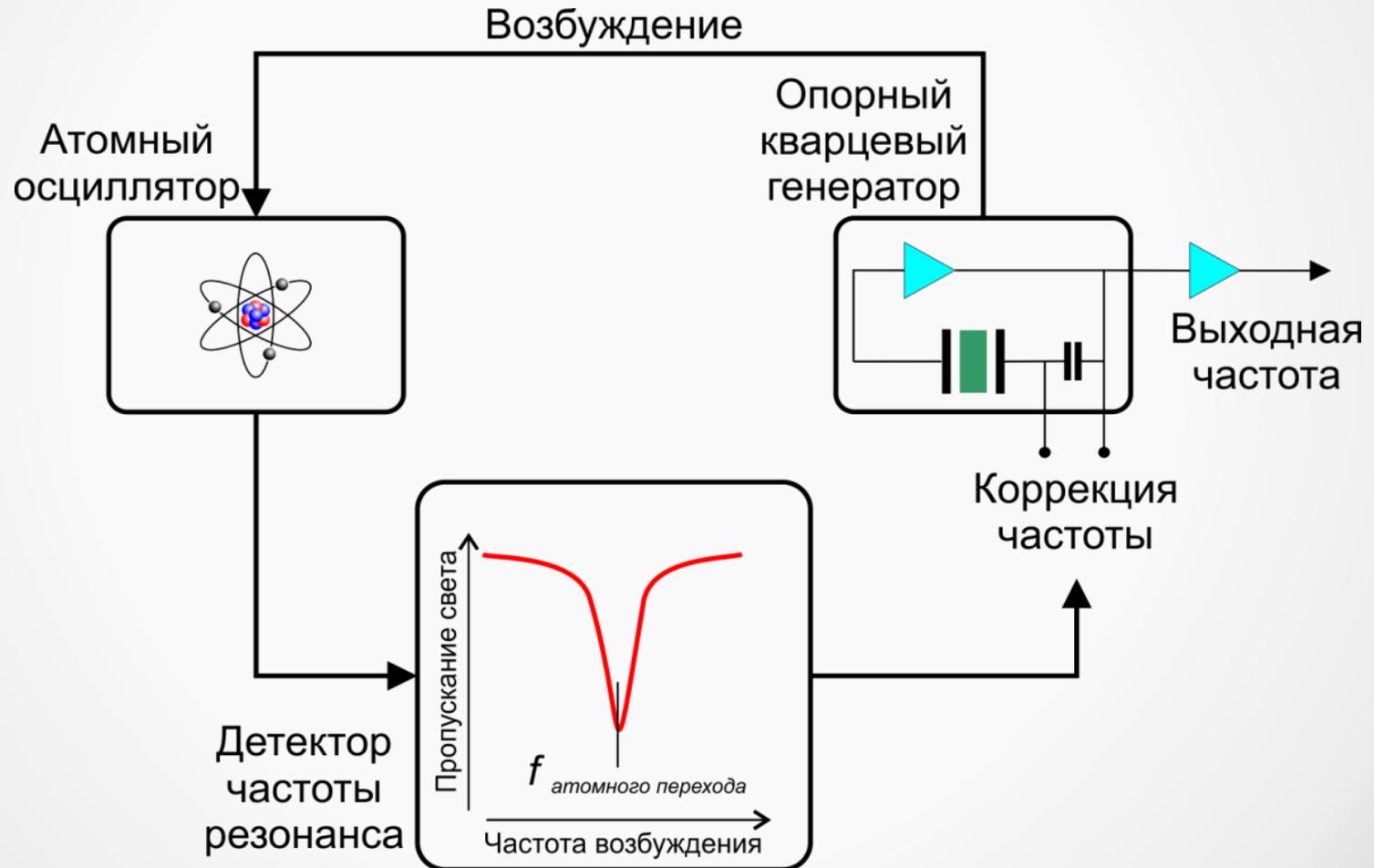


China, 50cm<sup>3</sup>, 6W



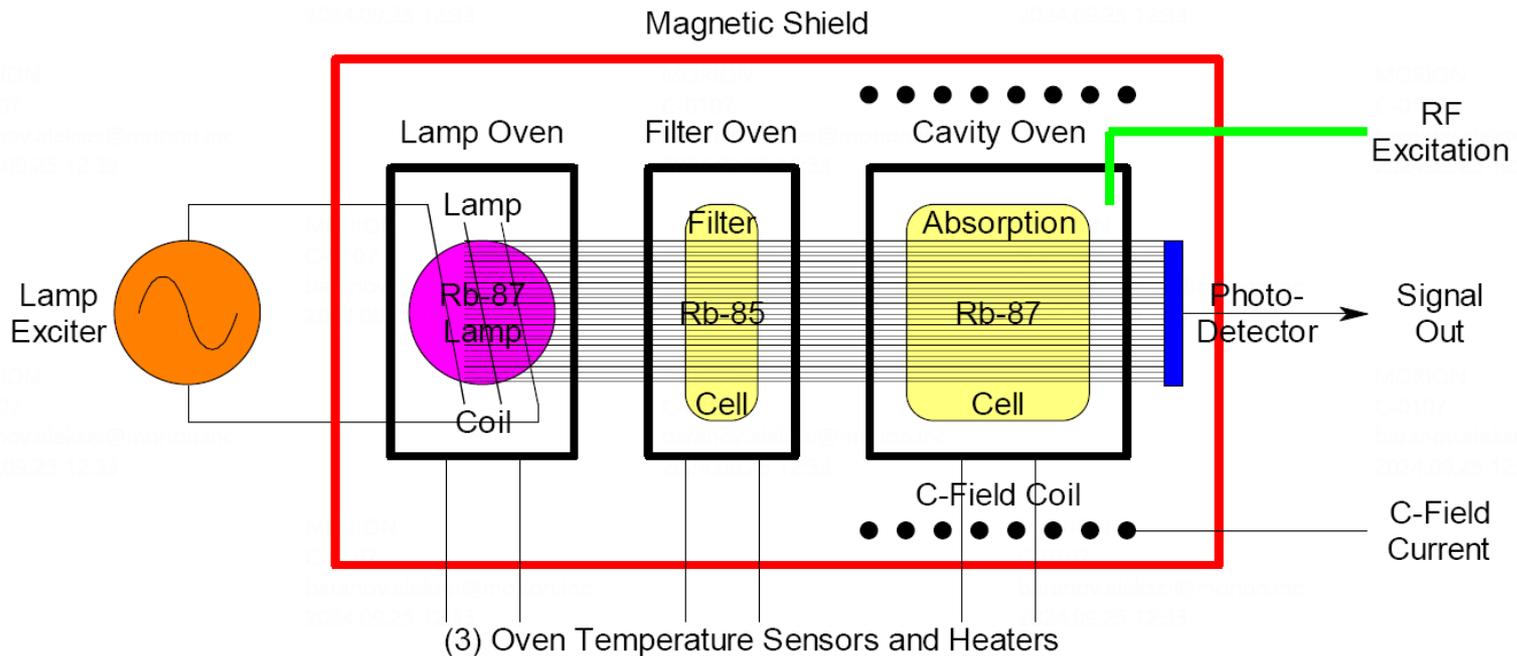
FR, 50cm<sup>3</sup>, 0.5W

# Принцип работы пассивных атомных часов

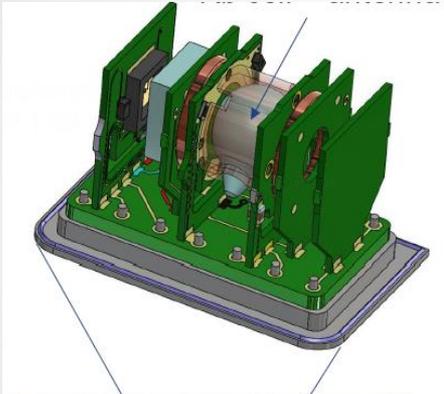


# Физический модуль

## Rb Gas Cell Physics Package



# MAC – миниатюрные атомные часы



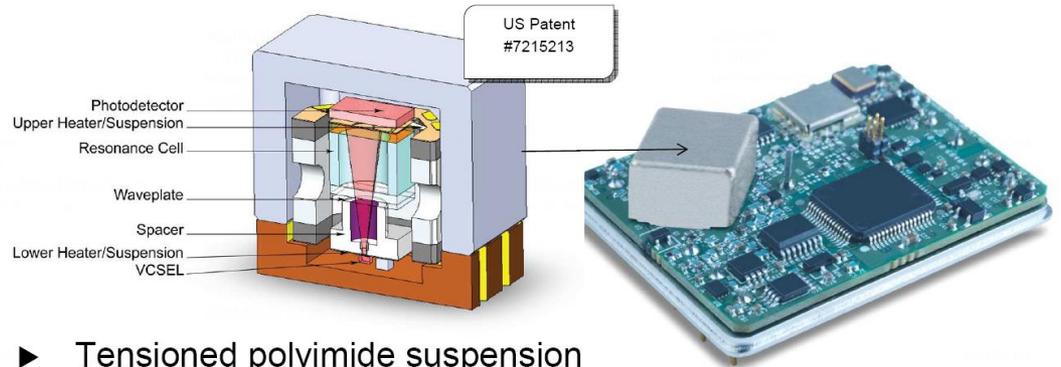
SA.5X – from November 25, 2019



Morion RFS-M102

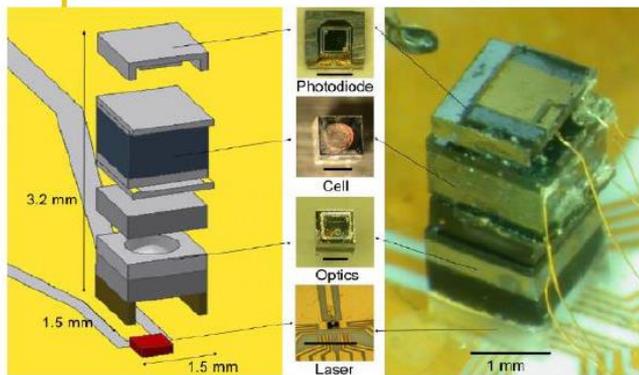
# CSAC

4x3.5x1.2cm - 17cm<sup>3</sup> - 35g - 120mW

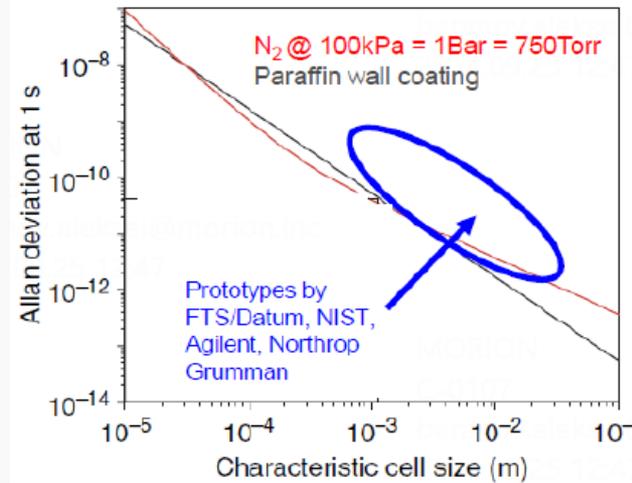


- ▶ Tensioned polyimide suspension
- ▶ Microfabricated silicon vapor cell

Smaller cell  $\rightarrow$  Higher  $ADEV(\tau) = \frac{1}{Q \times SNR} \tau^{-\frac{1}{2}}$



S. Knappe (NIST), "A microfabricated atomic clock", Applied Physics Letters, 2004



Дрейф частоты  $\sim 9E-10$ /месяц!!!

# ЭКОНОМИКА

Technology	Units/year	Unit price, typical range	Worldwide sales, \$/year	Performance
Quartz crystals	~5x10 <sup>9</sup>	~\$0.1 to \$2,000	~\$5B	Very low to medium
CSACs	~12,000 (?)	~\$500 (?) to \$5000 (?)	~\$15M (?)	Medium
Rubidium cells	~30,000	~\$1,000 to \$10,000	~\$150M	High
Caesium beam	~500	~\$40,000 to 100,000	~\$40M	Very high
Hydrogen masers	~20	More than ~\$100,000	~\$4M	The best

## Rubidium Oscillator

PRS10 — Low phase noise Rb oscillator

PRS10... from \$1895

BUY / QUOTE



- <-130 dBc/Hz phase noise (10 Hz)
- 1 pps input
- 72 hour Stratum 1 level holdover
- RS-232 for diagnostics & control
- 20 year lamp life

0.3W, CPT inside!

090-03054-000

090-03054-000-ND  
Microchip Technology  
XTAL OSC ATOMIC 10.0000MHZ 50WV  
10MHz Atomic Sine Wave Oscillator 3.3V Module  
8 Weeks

Features

- Power consumption <295 mW
- Less than 46 cc volume, 2.0" × 2.0" × 0.73"

Applications

- Underwater sensor systems
- GPS receivers
- Dismounted radios
- Dismounted IED jamming systems
- Autonomous sensor networks
- Unmanned vehicles

Documents & Media

Datasheets 090-03054-000

PRICE BREAK UNIT PRICE

PRICE BREAK	UNIT PRICE
1	5,217.30000

EXTENDED PRICE

€5.217,30

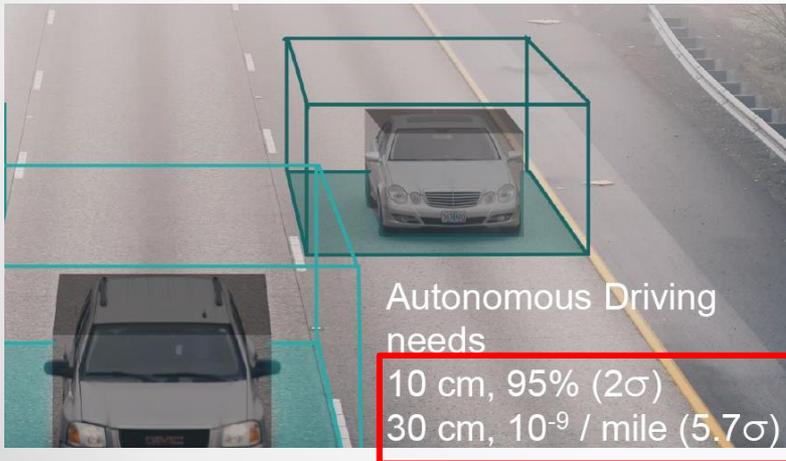
32



# Требования к погрешности синхронизации

	200 nsec	400 nsec	1.1 usec	1.5 usec	5 usec	10 usec
HQOCXO	10 hours	17 hours	1.5 days	2.2 days	4.4 days	6.6 days
Rubidium	1 days	1.8 days	3.5 days	4 days	8 days	12 days

Stratum level	Stratum-1	Stratum-2	Stratum-3E	Stratum-3
Frequency accuracy	$1.0 \times 10^{-11}$	$1.6 \times 10^{-8}$	$1.0 \times 10^{-6}$	$4.6 \times 10^{-6}$
Frequency stability	N/A	$1.0 \times 10^{-10}$	$1.0 \times 10^{-8}$	$3.7 \times 10^{-7}$
Time offset per day	0.864 $\mu$ s	8.64 $\mu$ s	864 $\mu$ s	32 ms
Interval between cycle slips (i.e. time offset > 62.5 $\mu$ s)	72 days	7.2 days	104 minutes	3 minutes
Typical frequency standard	Cesium Rubidium, with periodic calibration	Rubidium MAC High Quality OCXO	CSAC OCXO	OCXO TCXO



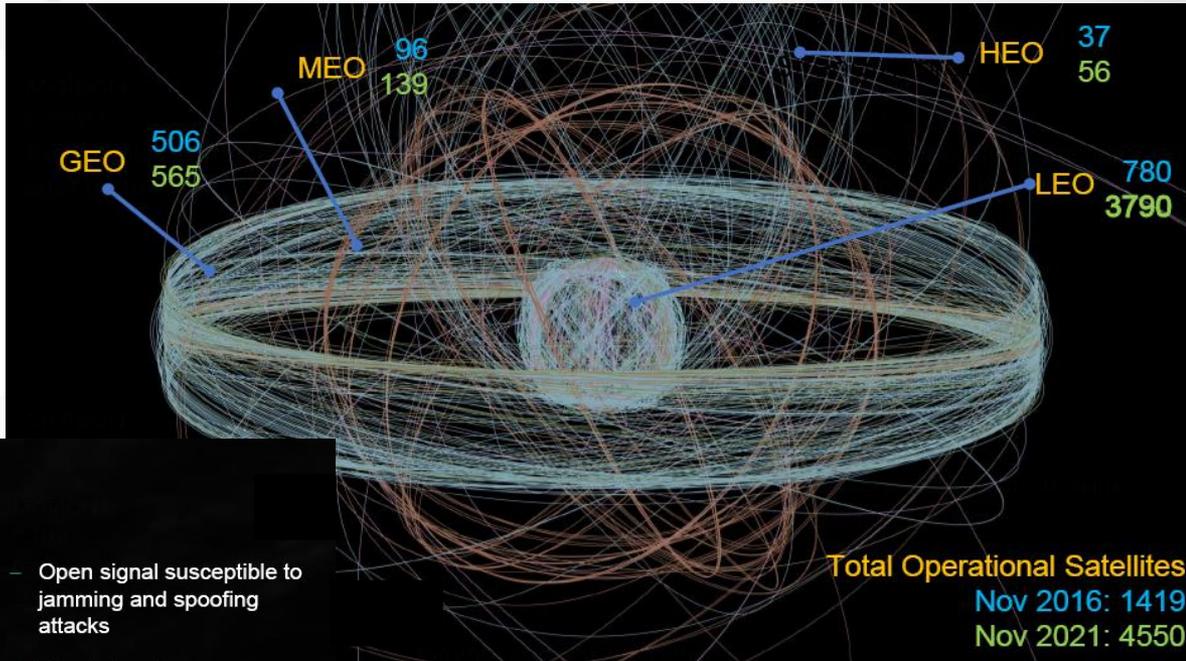
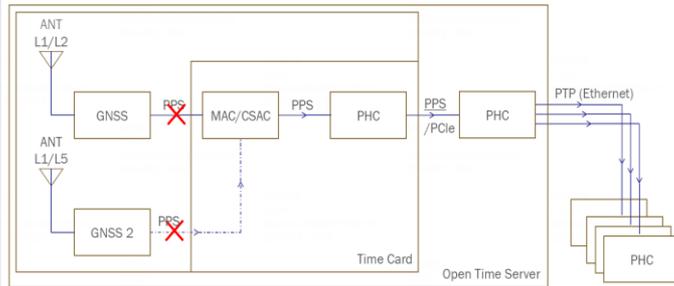
## Use Case: Distributed AI

- Resource Intensive to move data to one machine or cluster
- With the right precision, you can train in many places
- Then use the timestamps to merge the results
- Advantages:
  - Reduces data center traffic/congestion
  - Save Resources
- Requires end-to-end precision of <100ns
  - Across the data center
  - Globally



# Проблемы GNSS синхронизации

Control Flow In Holdover



**The New York Times**  
**America Has a GPS Problem**  
The system is essential but also vulnerable. We need a backup.  
By Kate Murphy  
Jan. 23, 2021

**DHS Believes Our Reliance on GPS 'Poses a Risk to National Security'**

**GPS at risk: Those signals are more vulnerable than you realize**

**Why Doesn't GPS Work Inside a Building?**

**The entire global financial system depends on GPS, and it's shockingly vulnerable to attacks**

- Open signal susceptible to jamming and spoofing attacks
- Weak signal very vulnerable to interference, cannot penetrate buildings
- Regulations already forming (EO 13905) to require GPS alternatives / backups on critical infrastructure

# Режим удержания (Holdover)

1

2

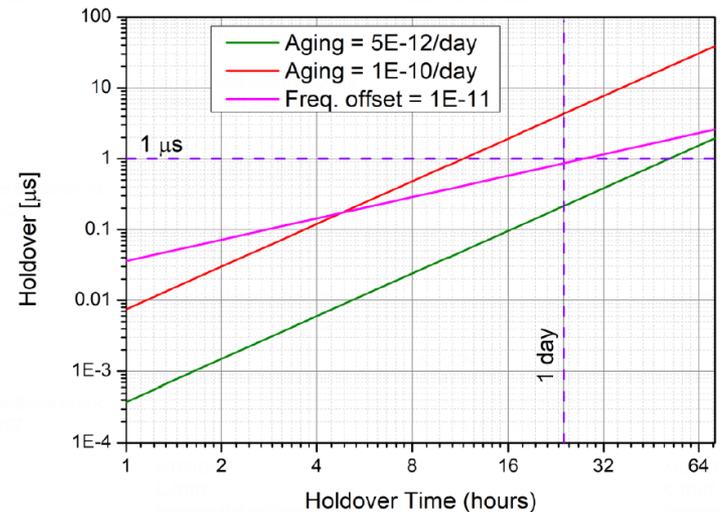
3

4

5

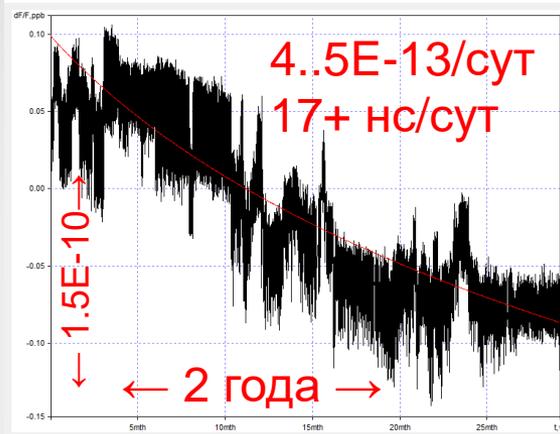
$$\Delta T(\tau) = T_0 + \frac{\Delta f}{f} \tau + \frac{1}{2} A \tau^2 + \sigma_x(\tau) + \epsilon(\tau)$$

1. Time-offset (synchronization)
2. Frequency-offset (syntonisation)
3. Frequency-aging
4. Statistical fluctuations (TDEV)
5. Environmental fluctuations
  - a) Temperature
  - b) Pressure
  - c) Acceleration, vibration, shock, 2g-tipover
  - d) Radiation
  - e) ....



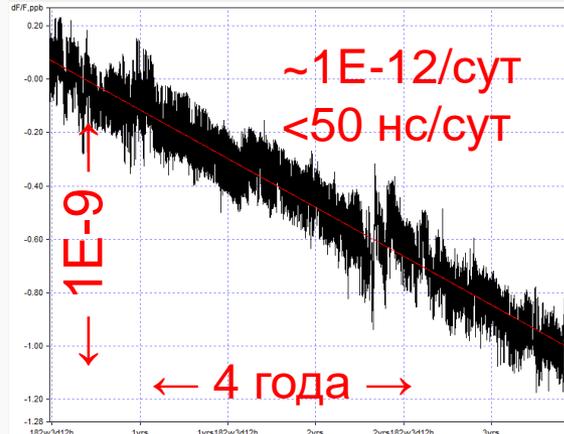
# Дрейф частоты (Aging)

RFS-M102



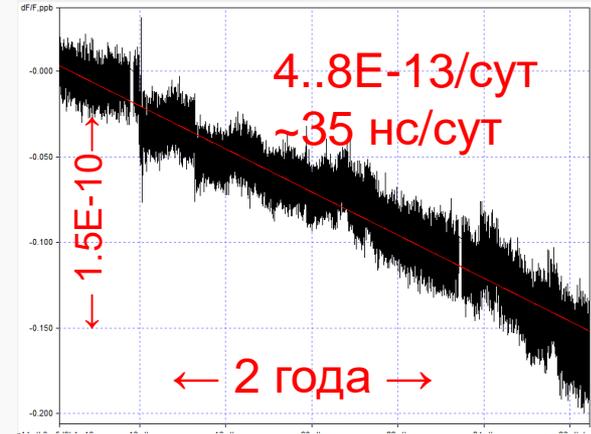
Start day: 06.04.2022 14:56; End day: 28.08.2024 18:22; 875 days total;  
Ref.meas 10MHz, F0=0.00000  
30 days (forecast): -0.00038 ppb per day  
30 days (forecast): -0.01110 ppb per month  
30 days (forecast): -0.09921 ppb per year  
30 days (forecast): -0.35267 ppb per 10 years  
Forecast formula: 0.10-0.15Ln(t/364.98+1)  
Backcast: 0.00148ppb(last 5) 0.00027ppb(5-10)  
Backcast: 0.00053ppb(last 7)

FE-5680A



Start day: 08.04.2021 17:08; End day: 28.08.2024 18:27; 1238 days total;  
Ref.meas 10MHz, F0=0.00000  
30 days (forecast): -0.00103 ppb per day  
30 days (forecast): -0.03089 ppb per month  
30 days (forecast): -0.37580 ppb per year  
30 days (forecast): -3.75800 ppb per 10 years  
Forecast formula: 0.07-0.00t  
Backcast: 0.00630ppb(last 5) 0.01241ppb(5-10)  
Backcast: 0.00577ppb(last 7)

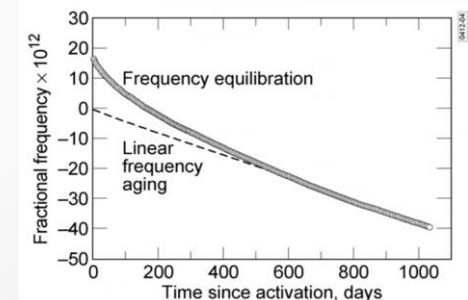
FE-5650A



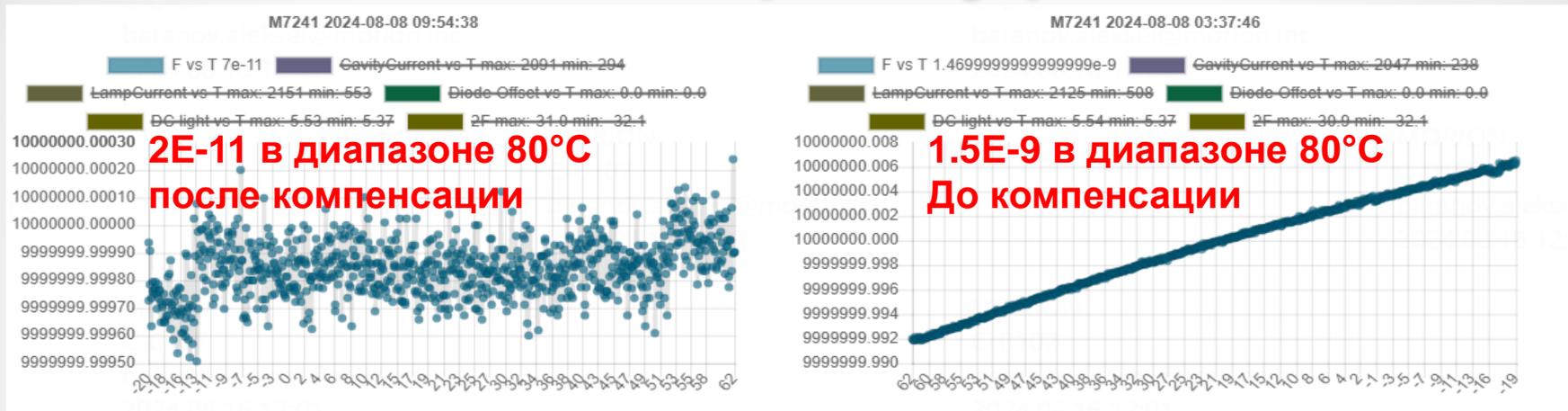
Start day: 27.06.2022 09:26; End day: 28.08.2024 18:31; 793 days total;  
Ref.meas 10MHz, F0=0.00000  
30 days (forecast): -0.00042 ppb per day  
30 days (forecast): -0.01259 ppb per month  
30 days (forecast): -0.15315 ppb per year  
30 days (forecast): -1.53154 ppb per 10 years  
Forecast formula: 0.00-0.00t  
Backcast: 0.00003ppb(last 5) 0.00002ppb(5-10)  
Backcast: 0.00083ppb(last 7)

- 1
- 2
- 3
- 4
- 5

$$\Delta T(\tau) = T_0 + \frac{\Delta f}{f} \tau + \frac{1}{2} A \tau^2 + \sigma_x(\tau) + \epsilon(\tau)$$



# Зависимость частоты от температуры



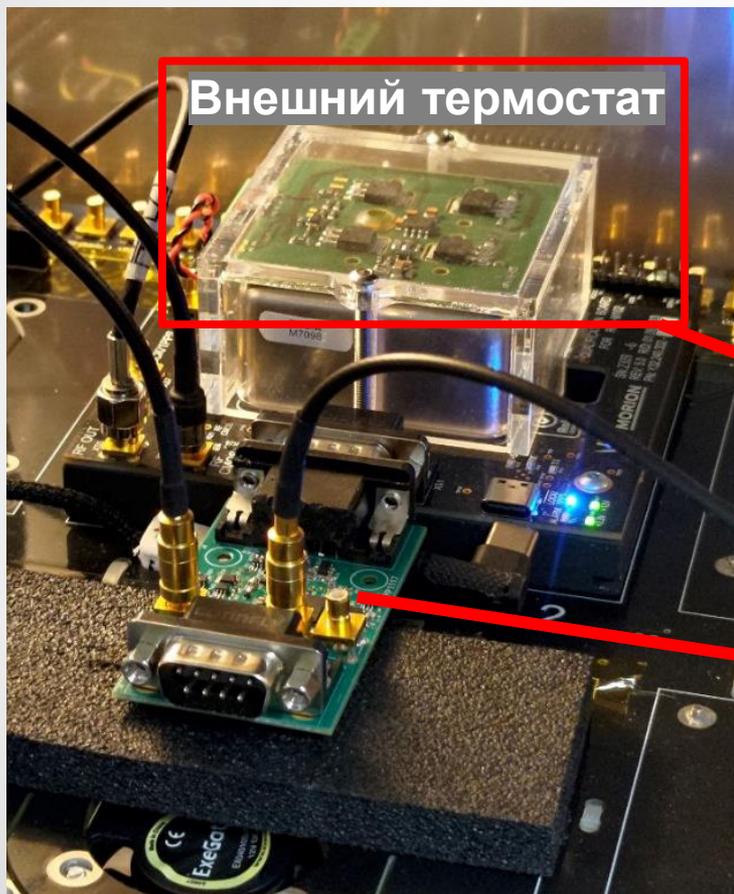
- Гистерезис менее 1E-12
- 2E-11 в диапазоне температур 80 градусов
- ТЧХ на 1-2 порядка больше суточного старения

1 2 3 4 5

$$\Delta T(\tau) = T_0 + \frac{\Delta f}{f} \tau + \frac{1}{2} A \tau^2 + \sigma_x(\tau) + \epsilon(\tau)$$

# RFS-M102 с внешним термостатом

RFS-M102



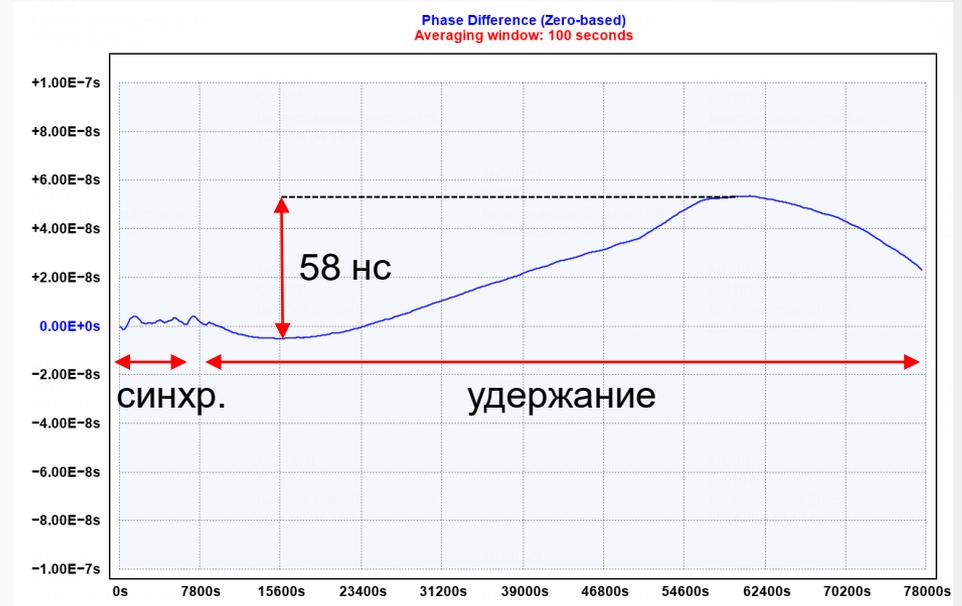
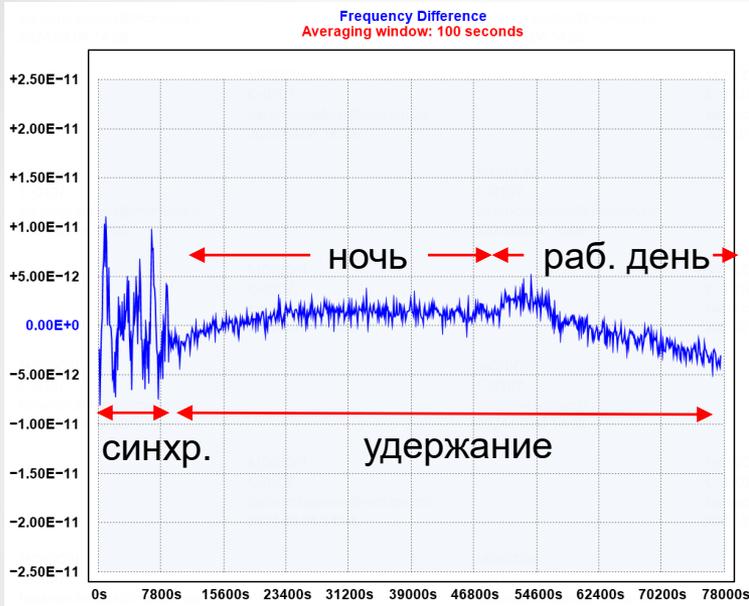
FE-5650A



$$\Delta T(\tau) = T_0 + \frac{\Delta f}{f} \tau + \frac{1}{2} A \tau^2 + \sigma_x(\tau) + \epsilon(\tau)$$

The equation is presented with five numbered boxes above the terms: 1 above  $T_0$ , 2 above  $\frac{\Delta f}{f} \tau$ , 3 above  $\frac{1}{2} A \tau^2$ , 4 above  $\sigma_x(\tau)$ , and 5 above  $\epsilon(\tau)$ . Red boxes are drawn around the terms  $T_0 + \frac{\Delta f}{f} \tau$  and  $\epsilon(\tau)$ . Red arrows point from the thermostat enclosure in the RFS-M102 image to the first red box, and from the FE-5650A image to the second red box.

# Результаты удержания фазы



FE-5650A производства АО Морин

# Выводы

- Рубидиевые генераторы могут выступать «хранителем фазы» с погрешностью менее 100 нс в сутки
- Стабильность температурного режима (или термокомпенсация) генератора вносит наибольший вклад в погрешность частоты на суточном интервале.
- Точность сличения частот и фаз имеет принципиальное значение для обеспечения заданной погрешности, но не является характеристикой конкретного вида генератора (т.е. справедливо для любого источника)

**СПАСИБО ЗА  
ВНИМАНИЕ**