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"State of the art atomic frequency standards and prospects for future: A Report of European Activities"

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Introduction

This report concerns the european activities on the following subjects:

1) State of the art frequency standards for ground or space applications which are presently available or which will be available in near future (optical frequency standards are not considered)

2) European experiments involving space atomic clocks

3) Basic research development trends in Europe.

In the following we give only a short description. More details can be obtained directly from the author.

1. Activities in Europe (including Russia) covers all the field of the frequency standards. The performances of the standards presently available (or available in near future) are summarized in the following table (1 to 8).

I. Appenzeller (ed.), Highlights of Astronomy, Vol. 10, 266–276.

1 State of the art quartz crystal oscillators for ground use (European Sources)

Manufacturer	Oscilloquartz S.A. Neuchâtel, Switzerland	BVA Industrie Besançon, France
Resonator type	BVA	Mini BVA
Output frequency	5 MHz	10 MHz
Phase noise L	1 Hz : - 115 dBc 10 : - 140 > 100 : - 150	1 Hz : - 110 dBc 1000 Hz : - 155 dBc
Frequency stability $\sigma(\tau)$	τ = 1-100 s : $5x10^{-13}$	τ = 1-10 s : < $1x10^{-12}$
Temperature coefficient	$1x10^{-12}$/°C	$5x10^{-12}$/°C
Aging	$2x10^{-11}$/day	< $1x10^{-10}$/day
g-sensitivity	< $1x10^{-9}$/g	< $2x10^{-10}$/g
Power consumption	4.5 W	2.5 W
Volume	0.82 l	0.095 l
Weight	0.85 kg	0.1 kg
Price	2 kAU 3.5 kSFR	1.15 kAU 2 kSFR

2. State of the art quartz oscillators for space use

(presently available or available in near future from European Sources)

Manufacturer	CIR, Gals Switzerland DRS/Artemis	CEPE, Argenteuil France Telecom II and DORIS/TOPIX	Observatory Neuchâtel Master Oscillator (under development)
Resonator type	*Mini BVA*	QAS	*Mini BVA*
Output frequency	5 MHz	10 MHz	10 MHz
Phase noise			
0.5 Hz	- 107 dBc	1 Hz: - 120 dBc	1 Hz: - 105 dBc
5 Hz	- 136	10: - 140	10 : - 130
100 Hz	- 146	100: - 148	100: - 150
1000 Hz	- 152	1000: - 155	1000: - 150
10'000 Hz	- 152	10'000: - 155	10'000: - 155
Frequency stability $\sigma(\tau)$	4.1×10^{-13} $\tau = 1$ s	5×10^{-13} $\tau = 1 - 100$ s	$< 1 \times 10^{-12}$ $\tau = 1 - 100$ s
Temperature coefficient			$< 2 \times 10^{-12}/°C$
Aging	1×10^{-10}/day		$< 3 \times 10^{-11}$/day
g-sensitivity			$< 2 \times 10^{-10}$/g
Power consumption	7W		3W
Volume	1.33 *l*	*0.72 l*	*0.15 l*
Weight	1.6 kg	1.2 kg max	0.15 kg
Lifetime		10 years	
Price		100 kAU for 1/5 units (175 kSFr)	

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3 Rubidium oscillators for ground use (European Sources)

Manufacturer	Rohde+Schwarz Munich, Germany	RIRT St. Petersburg Russia	Observatory Neuchâtel Switzerland
Output frequency	5 MHz	5 MHz	10 MHz
Phase noise	≥ 100 Hz : ≥ - 125 dBc		1 Hz : - 80 dBc 10 : - 120 100 : - 120 1000 : - 140 10'000 : - 145
Frequency stability $\sigma(\tau)$	$6\times10^{-12}\times\tau^{-1/2}$ τ = 1 s ÷ 100 s (atomic resonator limitation)	$1\text{-}2\times10^{-11}$ τ = 1 - 100 s $2\text{-}5 \times 10^{-12}$ τ = 100 - 1000 s	$4\times10^{-12}\times\tau^{-1/2}$ τ = 1 - 100 sec
Temperature coefficient	2×10^{-12}/°C	2×10^{-12}/°C	< 4×10^{-12}/°C
Temperature range	- 20 to + 45°C	- 30 to + 55°C	- 20 to + 65°C
Frequency drift	≤ 1×10^{-11}/month	5×10^{-12}/month	< 4×10^{-11}/month
g-sensitivity			< 1×10^{-11}/g
Power consumption	17 W	35 W	< 8 W
Volume	5,15 l	16 l	0.26 l
Weight	3.7 kg	12.5 kg	0.47 g
Lifetime			
Price kAU Price kSFr	~ 20 kAU 35 kSFR		~ 3 kAU 5 KSFR

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4 Rubidium oscillators for space use (European Sources)

Manufacturer	RIRT Russian Institute of Radionavigation and Time, St. Petersburg, Russia	Observatory of Neuchâtel, Neuchâtel, Switzerland
Output frequency	5 MHz	5 MHz / 10 MHz / 20 MHz
Frequency stability $\sigma(\tau)$	$2 \times 10^{-11} \times \tau^{-1/2}$	τ = 1 s : 4×10^{-12} 10 s : 1×10^{-12} 100 s : 4×10^{-13}
Temperature coefficient	3×10^{-12}/°C	< 4×10^{-12}/°C
Temperature range	5 - 45°C	- 25 to + 60°C
Frequency drift	< 10^{-11}/month	1×10^{-11}/month
g-sensitivity		< 4×10^{-12}/g
Power consumption	20 W	7.5 W
Size	120 x 268 x 300 m (~ 10 l volume)	1.2 l volume
Weight	8 kg	1.3 kg
Lifetime	4 years	7.5 years
Price		230 kAU (140 kAU + HR components) 400 kSFR (250 kSFR + HR components)

5 Cesium oscillator for ground use (European Sources)

Manufacturer	Oscilloquartz S.A. Neuchâtel, Switzerland
Output frequency	10 MHz
Frequency stability $\sigma(\tau)$	τ = 1-10s : $2x10^{-11}$ 100 : $1x\ 10^{-11}$ 1000 : $3x10^{-12}$ 10'000 : $1x10^{-12}$
Temperature coefficient	$5x10^{-14}$/°C
Temperature range	- 30 to + 70°C
Accuracy	± $5x10^{-12}$
Frequency drift	± $3x10^{-12}$ for life of Cs tube
Power consumption	24 W
Size	12 l
Weight	10 kg
Lifetime	> 10 years
Price	36 kAU 63 kSFR
Model	3020 EUDICS

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6 Cesium oscillator for space use (European Sources)

Manufacturer	RIRT Russian Institute of Radionavigation and Time, St. Petersburg, Russia	
Models	Malakhit	USPEKH TUBE (in development)
Output frequency	5 MHz	
Frequency stability		
$\sigma(\tau)$ 1 s	2×10^{-11}	1×10^{-11}
100 s	5×10^{-12}	1×10^{-12}
1 hour	5×10^{-13}	1×10^{-13}
1 day	1×10^{-13}	2×10^{-14}
Temperature coefficient	2×10^{-13}/°C	
Temperature range	0 - 40°C	
Accuracy	$\pm 1 \times 10^{-11}$	
Power consumption	90 W	
Size	414 x 421 x 655 mm	
Weight	52 kg	
Expected lifetime	3.25 years	
Price		

7 H-Maser frequency standards for ground use (European Sources)

Manufacturer	Observatory of Neuchâtel CH-2000 Neuchâtel	IEM KVARZ and VREMYA Nishnij Novgorod, Russia
Output frequency	5, 10, 100 MHz	5 and 100 MHz
Frequency stability	(with cavity autotuning)	
$\sigma(\tau)$ $\tau =$ 1 s	$\leq 8.3 \times 10^{-14}$	4×10^{-13}
10 s	$\leq 1.7 \times 10^{-14}$	4×10^{-14}
100 s	$\leq 5 \times 10^{-15}$	8×10^{-15}
1000 s	$\leq 2 \times 10^{-15}$	3×10^{-15}
10'000 s	$\leq 7 \times 10^{-16}$	3×10^{-15}
Phase noise L	(5 MHz)	
1 Hz	- 115	- 120 dBc
10	- 140	- 130
100	- 153	- 140
1000	- 156	- 150
10'000	- 156	- 150
Frequency drift	$\leq \pm 2 \times 10^{-14}$/day	$\leq \pm 1 \times 10^{-14}$/day
Temperature coefficient	$\leq 2 \times 10^{-14}$	$\leq 5 \times 10^{-15}$/°C
Temperature range	20 - 30°C	20 - 30°C
Magnetic field coefficient	$< 2 \times 10^{-14}$/G	$< 1 \times 10^{-14}$/G
Power consumption	~ 200 W	100 Wmax
Size (mm)	560 x 1100 x 1250	650 x 500 x 450
Volume	770 l	146 l
Weight	260 kg	80 kg
Lifetime	> 10 years	
Price (kAU)	143 kAU	86 kAU
(KSFr)	250 kSFR	150 kSFR

8 H-Maser frequency standards for space use (European Sources)

Manufacturer	Observatory of Neuchâtel CH-2000 Neuchâtel	IEM KVARZ and VREMYA Nishnij Novgorod, Russia
Output frequency	10 MHz, 100 MHz	1 Hz, 5 MHz, 100 MHz
Frequency stability		
$\sigma(\tau)$ $\tau =$ 1 s	1.5×10^{-13}	5×10^{-13}
10 s	2.1×10^{-14}	5×10^{-14}
100 s	5.1×10^{-15}	1.5×10^{-14}
1000 s	2.1×10^{-15}	5×10^{-15}
10'000 s	1.5×10^{-15}	1 day $3 \cdot 10^{-15}$
Phase noise L		
1 Hz	- 95 dBc	
10	- 120	
100	- 130	
1000	- 140	
10'000	- 150	
100'000	- 150	
Frequency drift	$< 1 \times 10^{-14}$/day	$< 1 \times 10^{-15}$/day
Temperature coefficient	$\leq 1 \times 10^{-14}$/°C	5×10^{-15}/°C
Temperature range	20 to 35°C	5 to 40°C
Magnetic coefficient	$\leq 2 \times 10^{-14}$/G	$< 1 \times 10^{-14}$/G
Power consumption	≤ 60 W	80 W
Size (mm)	Ø 460, 600 high	550 x 480 x 300
Volume	~ 90 l	~ 80 l
Weight	≤ 50 kg	50 kg
Lifetime	> 5 years	
Price	600 kAU 1 MSFR	

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2. European experiments involving space clocks

Space atomic clocks in Europe are developed mostly at the Russian Institute of Radionavigation and Time (RIRT), St.Petersburg, Russia, in connection with the GLONASS system and at the Observatory of Neuchatel (ON), Switzerland for European Space Agency programs.

Radioastron 1. This is an Orbiting VLBI experiment based on the Russian satellite Radioastron with an important international participation. Two space clocks from the ON will be used on board of Radioastron 1.

An H-Maser, used as local oscillator, during part of the experiment allowing coherence time up to several thousands seconds.

A Rubidium Ultrastable Oscillator, used as general backup oscillator.

In addition, the originally planed system for transferring the phase of ground H-masers to the satellite is available. This configuration allows to perform a relativistic experiment, called Clock Relativity Observation of Nature of Space time (CRONOS) which consists in a redshift measurement with an expected accuracy of $\leq 1x10^{-6}$.

The use of retroreflectors on board is presently under discussion, for laser time transfer and for better determination of the atmospheric delay.

METEOR III M. This is a Russian Earth Observation Satellite in polar orbit which could hold a package of two H-masers (one from the Russian Institute VNIIFTRI near Moscow and one from the ON) with additional instrument on board as the PRARE system, a phase carrier GPS receiver and a LASSO type package.

This experiment called Timing Ranging and Atmospheric Sounding (EXTRAS) has the following objectives: technology demonstration of Space H-Masers, time dissemination and time transfer with ~ 10 psec accuracy, positioning with millimetric precision, laser time transfer and GPS satellite occultation experiment for atmospheric parameters determination.

3. Basic research development in Europe

Trends in basic research. The European Frequency and Time Forum in March 1994, Munich, has offered the opportunity for a good overview of the present basic research effort in Europe (Proceedings of the 8th European Frequency and Time Forum, Munich, March 1994, available from VDI, Postfach 11 11 39, D-40002 Düsseldorf, Germany).

Rubidium: Progress has been presented in the laser pumped gas cell Rubidium (ON) and future development in this field appears promising.

H-Maser improvements concern mostly the autotuned H-Masers long term drift (NIST, BIMP, PTB). Drift of $< 1x10^{-16}$/day are repeatedly achieved. Such selected masers are already improving the TAI time scale for period up to few months.

Studies on cold H-Maser are also in progress at the NPL, Teddington, UK.

Cesium experiments on cooling of Cs atoms by laser are performed in several laboratories. The most interesting results are from the Laboratoire Primaire Temps et Fréquence (LPTF) in Paris and concern the atomic fountain:

short term stability $\sigma_y(\tau) = 6x10^{-13}x\tau^{-1/2}$ $\tau \leq 1$ hr

projected accuracy $< 3x10^{-15}$

Finally interesting results on laser pumped Cs beam [primary standards (LPTF), industrial type standards (Laboratoire de l'Horloge Atomique, Paris)] have been recently obtained.

In conclusion laser cooling of Cs atoms appears to be the most promising and developing field in the basic research of atomic frequency standards.

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