Application Note

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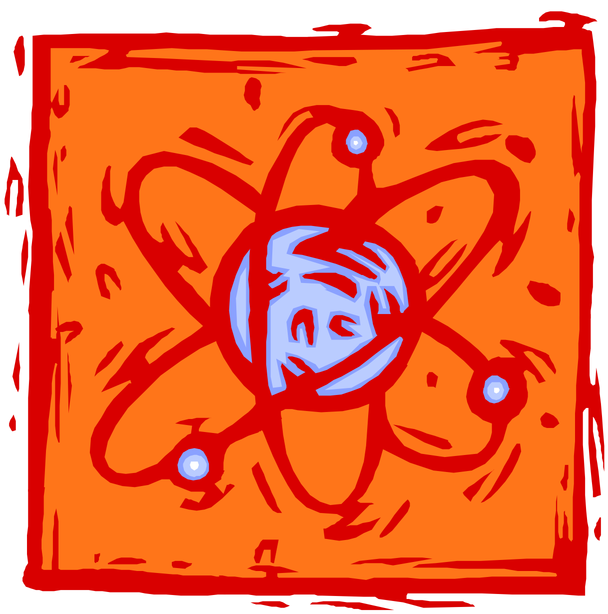
Cesium Clock and Hydrogen Maser Compared



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1 Introduction

This Application Note compares two technologies often used as frequency sources in applications where highest frequency accuracy and stability are required. Cesium Clocks have been around for almost 50 years. They are not only used in industrial applications such as telecommunications or measurement, but most importantly they are used as standard references for the definition of time and frequency units as well as for the generation of international time scales. Hydrogen Masers started to appear in commercial versions more recently. The main reason for the recent interest in their development is better short term stability. There exist two different types of Hydrogen Masers, the so-called active ones, and the passive ones. In active Hydrogen Masers the microwave oscillation in the hydrogen filled cavity is self-sustained; in the passive ones, a microwave signal is injected into the cavity. This Application Note considers only the more compact and less expensive Passive Hydrogen Masers. In order to make it easier to compare things, a number of real Cesium Clock and Hydrogen Maser products are compared in terms not only of performance, but also of operational aspects. Chapter 4 considers the particular case of telecom applications. In telecommunication networks so-called Primary Reference Clocks (PRC) are used for the synchronization of network equipment. The performance specifications of Cesium Clocks and Hydrogen masers are compared with the relevant PRC standards.

2 Performance

This chapter compares the performance of Cesium clocks and Hydrogen Masers. The comparison is based on two Oscilloquartz Cesium clocks and two Oscilloquartz Hydrogen Masers. The specifications of these four product types are summarized in Table 1. The two Cesium clocks are the Long Life and the High Performance versions of the OSA 5585 PRS. The two Hydrogen Masers are the OSA-VCH 1006 PHM and the OSA 3700 PHM. The OSA 5585 PRS Long Life and the OSA-VCH 1006 PHM are optimized for telecom applications. They comply with the relevant telecom standards for Primary Reference Clocks (PRC), while at the same time matching equipment practice and maintenance requirements of the telecom industry. The OSA 5585 PRS High Performance and the OSA 3700 PHM are optimized for highest performance. Typical applications are measurement, calibration, but also synchronization of satellite ground stations and the like.

The two most important performance parameters contained in Table 1 are also represented graphically in Figures 1 and 2. Figure 1 shows the Allan Deviation (ADEV) as a function of Observation Time Interval. ADEV for Observation Time Intervals of up to 1 day expresses the short term stability of a frequency source. The figure shows that in terms of short term stability the Hydrogen Masers perform better than the Cesium Clocks. This is the main advantage of Hydrogen Masers over Cesium Clocks.

Figure 2 shows frequency accuracy as a function of time. Frequency accuracy is usually defined as the maximum frequency deviation from the nominal frequency over the device's lifetime; it is expressed as a fractional frequency. Within this document frequency accuracy is divided into two terms, i.e. long-term stability and initial frequency accuracy. The latter accounts for all influences other than long-term stability, including influences of changing environmental conditions. Since long-term stability is dominated by frequency drift, it is possible to define a time-dependent frequency accuracy: Figure 2 shows the upper limit (maximum) of the 1 day moving average of fractional frequency as a function of time, and specified for the full environmental envelope (see Table 1 under "Operating Conditions"). In a controlled environment, especially in an environment with controlled temperature, the frequency accuracy is much better than what the curves show (frequency accuracies for controlled environments are given in Table 1).

Figure 2 shows that in the case of the Hydrogen Masers, frequency is affected by a noticeable frequency drift. The frequency drift is caused by the ageing of the inner coating of the maser's storage bulb. Cesium clocks do not exhibit any measurable frequency drift; this is why the curves for the two Cesium clocks are horizontal lines. The Hydrogen Maser's frequency drift specifications given in Table 1 and Figure 2 are only estimated, since there is not enough long-term experience with this product.

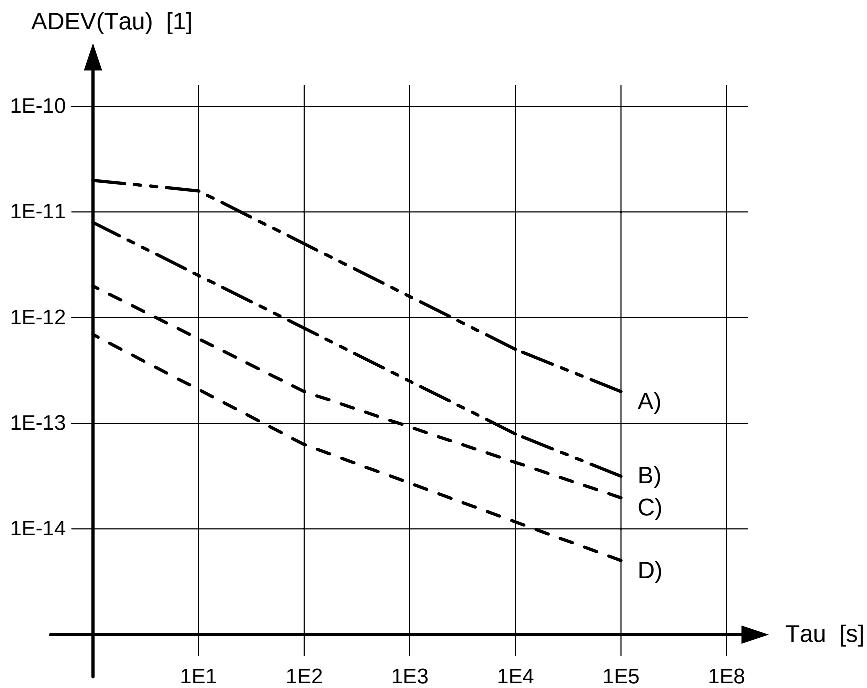
Table 1: Specifications

Parameter	Cesium Clocks		Hydrogen Masers	
	OSA 5585 PRS Long Life	OSA 5585 PRS High Performance	OSA-VCH 1006 PHM	OSA 3700 PHM
Initial Frequency Accuracy[1]				
Lab environment[2]	$\pm 5.0 \cdot 10^{-12}$	$\pm 2.5 \cdot 10^{-12}$	$\pm 1.0 \cdot 10^{-12}$	$\pm 3.0 \cdot 10^{-13}$
Full environment[3]	$\pm 7.0 \cdot 10^{-12}$	$\pm 3.5 \cdot 10^{-12}$	$\pm 2.0 \cdot 10^{-12}$	$\pm 6.0 \cdot 10^{-13}$
Long-term Stability (Frequency Drift)				
First 18 months[4]	0		$\pm 6.0 \cdot 10^{-14}$/month	
Thereafter[4]	0		$\pm 6.0 \cdot 10^{-15}$/month [5]	
Reproducibility[6]	$\pm 3.0 \cdot 10^{-12}$	$\pm 1.0 \cdot 10^{-12}$	Not specified	Not specified
Short-term Stability (Allan Deviation)				
τ = 1 s	$2.0 \cdot 10^{-11}$	$8.5 \cdot 10^{-12}$	$2.0 \cdot 10^{-12}$	$7.0 \cdot 10^{-13}$
τ = 10 s	$1.6 \cdot 10^{-11}$	$2.7 \cdot 10^{-12}$	$6.0 \cdot 10^{-13}$	$2.0 \cdot 10^{-13}$
τ = 100 s	$5.0 \cdot 10^{-12}$	$8.5 \cdot 10^{-13}$	$2.0 \cdot 10^{-13}$	$7.0 \cdot 10^{-14}$
τ = 1000 s	$1.6 \cdot 10^{-12}$	$2.7 \cdot 10^{-13}$		
τ = 3600 s			$6.0 \cdot 10^{-14}$	$2.0 \cdot 10^{-14}$
τ = 10,000 s	$5.0 \cdot 10^{-13}$	$8.5 \cdot 10^{-14}$		
τ = 100,000 s	$2.0 \cdot 10^{-13}$	$3.0 \cdot 10^{-14}$	$2.0 \cdot 10^{-14}$	$5.0 \cdot 10^{-15}$
Frequency Settability				
Range	$2.0 \cdot 10^{-9}$	$2.0 \cdot 10^{-9}$	$1.0 \cdot 10^{-10}$	$1.0 \cdot 10^{-10}$
Resolution	$1.0 \cdot 10^{-15}$	$1.0 \cdot 10^{-15}$	$1.0 \cdot 10^{-14}$	$1.0 \cdot 10^{-14}$
Power Consumption	85 W [7]		80 W	
Physical Properties				
Size	310 × 535 × 280 mm		200 × 470 × 513 mm	
Weight	25 kg		31 kg	
Operating Conditions				
Temperature	0 to 50 °C		5 to 40 °C	
Relative Humidity	95% up to 50 °C		80% up to 35 °C	
Atmospheric Pressure	15 (45) to 106 kPa [8]		84 to 106 kPa	
Magnetic Field	0 to 2 Gauss		0 to 2 Gauss	

Notes:
1) Expressed as a fractional frequency; without frequency drift
2) 22 ± 2 °C
3) As specified under “Operating Conditions”
4) Continuous operation
5) Estimated value
6) Ability to produce the same frequency when put into operation repeatedly without adjustments
7) 95 W during warm-up (30 min)
8) Performance specifications guaranteed for 45 to 106 kPA

As mentioned before, Table 1 contains the environmental conditions under which the specified performance is guaranteed (see “Operating Conditions”). The Caesium Clocks have wider operating ranges for temperature, humidity and atmospheric pressure. Hydrogen Masers are more sensitive to the environment because of the impact on the mechanically defined resonance frequency of the maser’s microwave cavity. Specified operating conditions need to be taken into consideration when choosing a frequency source for any given application.

It is important to note that Table 1 is based on the manufacturer’s performance specifications. In other words, values given in Table 1 are guaranteed upper limits (with the exception of the frequency drift values, which are estimated). Typical values are usually better than the specified ones.



A) Cesium Clock: OSA 5585 PRS Long Life

B) Cesium Clock: OSA 5585 PRS High Performance

C) Hydrogen Maser: OSA-VCH 1006 PHM

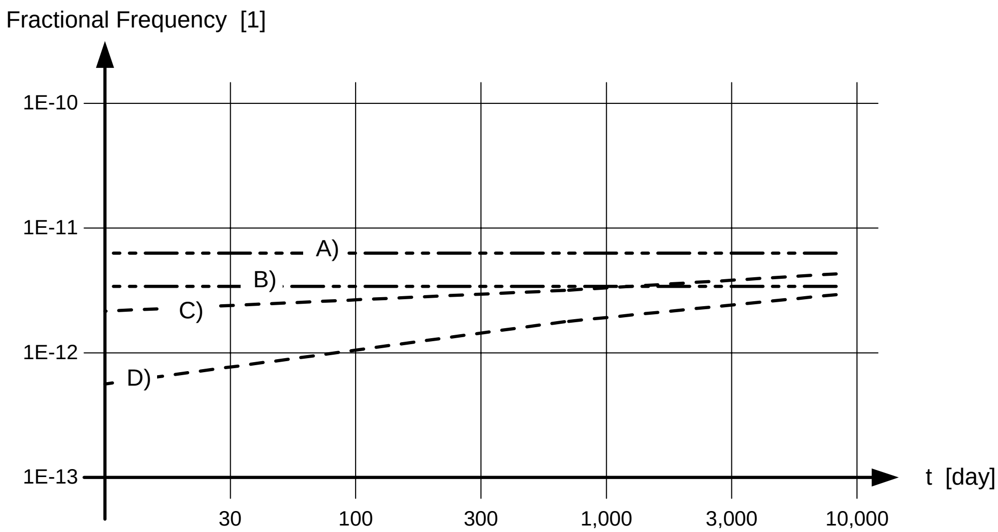
D) Hydrogen Maser: OSA 3700 PHM

Figure 1: Short Term Stability (Allan Deviation)

3 Operational Aspects

Product maintenance requirements have an important impact on overall product lifecycle costs. Cesium Clocks and Hydrogen Masers require some maintenance related to their physics packages. Besides this, there is no other scheduled maintenance required.

The lifetime of a Cesium tube is limited. In the case of the High Performance version, the specified lifetime of the tube is 7.5 years. In the case of the Long Life version, the specified lifetime is 12 years. These limits are caused by contamination of Cesium atom detectors inside the tube. In order to obtain acceptable lifetimes for the complete Cesium Clock, the design is made in such a way, that tubes can be replaced. Cesium tube replacement is the main maintenance operation that is needed. Given the fact that tube lifetimes are known, it is easy to plan for the replacement interventions ahead of time. Tube replacement must be done in the factory. Because tube lifetime is a critical factor, Oscilloquartz provides extended warranty periods for the tubes. These components come with a warranty period of 3 years[1] for the High Performance version, and 8 years[2] for the Long Life version.



A) Cesium Clock: OSA 5585 PRS Long Life

B) Cesium Clock: OSA 5585 PRS High Performance

C) Hydrogen Maser: OSA-VCH 1006 PHM

D) Hydrogen Maser: OSA 3700 PHM

Figure 2: Frequency accuracy (max. 1 day moving average) over full environmental envelope as a function of time

The case of the Hydrogen Maser is somewhat different. The main physical limitation is the consumption of the “fuel”, i.e. the hydrogen. The hydrogen tank’s capacity is designed for 5 to 6 years of continuous operation. In order to continue operation past this time period all that is required is refuelling the hydrogen tank. Here again, it is a good idea to plan for periodic refuelling ahead of time. The refuelling operation is usually done on site by a qualified technician. There is no need to send the unit back to the factory. The warranty period for the two Hydrogen Maser models is 3 years[3].

Given the fact that the physics packages can be replaced or refuelled, the overall product lifetime is mainly limited by lifetime limits of common electronics components. Expected lifetime is in the range of 15 to 20 years for the Cesium Clocks and 10 to 20 years for the Hydrogen Masers.

The main facts about product maintenance and lifetime are summarized in Table 2.

There are applications where a frequency source is used as a portable reference. An important aspect for such cases is the ease with which the source can be put into operation after having been transported. A Cesium Clock can be powered up immediately after transportation. Only 30 minutes after power-up the delivered frequency signal is already within performance specifications. This short and simple power-up and warm-up procedure makes the Cesium Clock an ideal portable reference source. A Hydrogen Maser requires some precautions. After transportation the maser must rest in the environmental conditions of operation for at least 8 hours. Only then is it allowed to power the unit up. This waiting time is required in order to let the maser’s physics package recover from the changes in environmental conditions during transportation.

Finally it should be noted, that Cesium Clocks may require special export licenses for some countries.

[1] Subject to change ; refer to product documentation
[2] Subject to change ; refer to product documentation
[3] Subject to change ; refer to product documentation

4 Telecom Requirements

Cesium Clocks and Hydrogen Masers make good Primary Reference Clocks for the synchronization of telecommunications networks. There are several standards specifying the performance of PRCs (see [2], [3] and [4]). All of them require a frequency accuracy of $\pm 1.0 \cdot 10^{-11}$ (measured over a time period of one week). Figure 2 shows that all four product types comply easily with this requirement (typical frequency accuracy is usually even better than the specified values). The standards also specify limits for short term stability (called wander in the telecommunication community). These specifications are not expressed as ADEV limits, but as TDEV and MTIE limits. Both versions of the OSA 5585 PRS Caesium Clock comply with the PRC wander generation requirement (refer to [5] for detailed specifications). Since the two Hydrogen Masers of this comparison exhibit even better short term stabilities than the Caesium Clocks, it is clear that the Hydrogen Masers also comply easily with the wander generation requirements.

Table 2: Product maintenance and lifetime

	Cesium Clocks		Hydrogen Masers	
	OSA 5585 PRS Long Life	OSA 5585 PRS High Performance	OSA-VCH 1006 PHM	OSA 3700 PHM
Periodic maintenance				
Operation	Cesium tube replacement		Hydrogen refuelling	
Location	Factory		On site	
Time period	12 years	7.5 years	5 to 6 years	
Product lifetime	15 to 20 years		10 to 20 years	
Warranty period				
Product	2 years		3 years	
Cesium tube	8 years	3 years	Not applicable	

5 Conclusions

The comparison between the two Cesium Clocks and the two Hydrogen Masers in the Oscilloquartz product line shows roughly the following:

- Cesium clocks and Hydrogen Masers have comparable frequency accuracies over the lifetime of the product
- Hydrogen Masers have better short term stabilities (ADEV) than Cesium Clocks
- Hydrogen Masers are affected by frequency drift
- Cesium Clocks require periodic Cesium tube replacements, whereas Hydrogen Masers only require periodic hydrogen refuelling
- Hydrogen Masers have tighter restrictions regarding environmental conditions (temperature, humidity, atmospheric pressure)
- Portability: after having been transported, Cesium Clocks can be used almost immediately, whereas Hydrogen Masers require a warm-up period before being put into operation.
- Cesium Clocks may require special export licenses for some countries

There are of course other differences. For some applications it is necessary to have a closer look to these finer differences. Some are contained in the specification overview of Table 1. Further details can be found in the product literature ([5], [6]). It should also be noted that the excellent performance characteristics of Cesium Clocks and Hydrogen Masers make both of them suitable for PRC applications in telecommunications networks; special attention must be paid to applicable environmental conditions in case Hydrogen Masers are used as PRCs.

6 Bibliography

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[2] ITU-T; *Recommendation G.811, Architecture of transport networks based on the synchronous digital hierarchy (SDH)*; Geneva; March 2000.

[3] ETSI; *EN 300 462-6-1: Generic requirements for synchronization networks; Part 6-1: Timing characteristics of primary reference clocks*; Sophia Antipolis; 1998.

[4] Telcordia; *GR-2830: Primary Reference Sources: Generic Requirements*; 1995.

[5] Oscilloquartz (company document); *Product Booklet, OSA 5585 PRS Primary Reference Source*; Neuchâtel; 2004.

[6] Oscilloquartz (company document); *Draft Product Datasheet, OSA-VCH 1006 Passive Hydrogen Maser*; Neuchâtel; 2005.

7 Abbreviations

Table 3: Abbreviations used in this Application Note

ADEV	Allan Deviation
ANSI	American National Standards Institute
AVAR	Allan Variance
Cs	Caesium
ETSI	European Telecommunications Standards Institute
H	Hydrogen
ITU-T	International Telecommunication Union, Telecommunication Standardization Sector
MASER	Microwave Amplification by Stimulated Emission of Radiation
MTIE	Maximum Time Interval Error
PRC	Primary Reference Clock
TDEV	Time Deviation