General Support Technology Program - GSTP

Miniaturized Timing Source - mTS

mTS Executive Summary

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TABLE OF CONTENTS

Page

1 INTRODUCTION 3

2 MTS CLOCK DESIGN AND PERFORMANCE 3

2.1 mTS CLOCK DESIGN 3

2.2 mTS CLOCK PERFORMANCE 5

3 COMMERCIAL EVALUATION 8

4 CONCLUSION AND DESIGN DEVELOPMENT PLAN 8

1 Introduction

Several studies have demonstrated the many advantages of miniature, very low power timing sources based on atomic clock technology. Such sources allow fast acquisition (e.g. for secured telecom with long spreading codes) and long coherent integration (e.g. for GNSS operation in interference or indoor environment).

Similarly, it has been shown that such sources would significantly improve the sensitivity of some on-board Earth Observation instruments (e.g. radiometers, radio-occultation). With many spacecraft manufacturers turning to commercial off-the-shelf (COTS) parts to meet performance, schedule and cost requirements, a commercial space mTS could provide a solution for LEO satellite missions.

Furthermore, it has been demonstrated that a timing source with very low power consumption could reduce dramatically the battery size, weight, and cost within sub-marine seismic recorders used for petrol research, sub-marine geological research, and sonar systems. Basically, any battery powered operation requiring precise timing without access to navigation signals or other external synchronization sources would benefit from such a low power timing source.

2 mTS clock design and performance

2.1 mTS clock design

Figure 2.1 shows the mTS clock with a total volume of 52x52x19 mm^3 (51 cm^3). Figure 2.2 shows the clock architecture with key components including the physics package (DIL-14 package), a 3 GHz VCO and a low power DSP microprocessor. A three-dimensional model of the physics package is shown in Figure 2.3. For ground applications, the PP power consumption is reduced by encapsulating all parts inside a DIL-14 package with a back-fill of 1.2 bar Xenon (reduced thermal conductivity compared to air). For space applications, the PP does not include the DIL-14 package as the clock will operate in vacuum (an optional DIL-14 with a small vent hole could be installed for protection against satellite outgassing contaminants). Also for space applications, the VCSEL (see below) will be hermitically sealed to protect the laser from any contaminants.

The mTS clock design is based on the “classical” rubidium clock heritage at Spectratime. However, to reduce power consumption and size, several modifications have been introduced including:

1. The plasma-lamp is replaced with a low power VCSEL (Figure 2.3, left)
2. The glass-blown vapor cell is reduced to a sphere with 5 mm diameter (Figure 2.3, center)
3. Several clock-functions are handled by a low power micro-controller (Figure 2.2, red box)
4. The 3 GHz microwave is generated with a VCO and fractional-N PLL (Figure 2.2, blue box)
5. The physics package (for ground applications) is encapsulated in a DIL-14 package with a 1.2 bar Xenon backfill (Figure 2.2, orange box)

The mTS clock includes several regulated supply voltages:

6. +5V for the PP heating and C-field,
7. +3.3V, +3V and +1.5V for the electronics package and remaining PP functions (VCSEL- and photo-diode supply).

On power-on the DSP firmware acquires the clock signal after 4 minutes warm-up. During normal operation several parameters are stabilized with servo-loops including:

8. VCSEL- and vapour cell temperature stabilized at nominal 75°C and 90°C (analogue, slow)
9. VCSEL wavelength stabilized to 795 nm via feedback to the VCSEL current (analogue, fast)
10. Quartz crystal (10 MHz) stabilized to clock resonance (3 GHz) via fractional-N PLL (digital, slow).

Figure 2.1: mTS clock unit (52x52x19 mm^3)

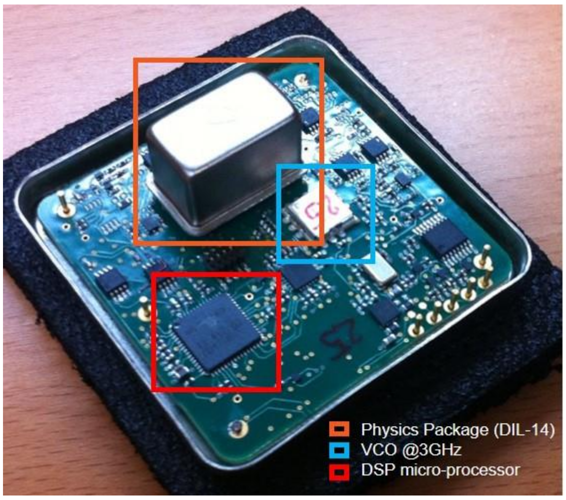


Figure 2.2: mTS clock architecture

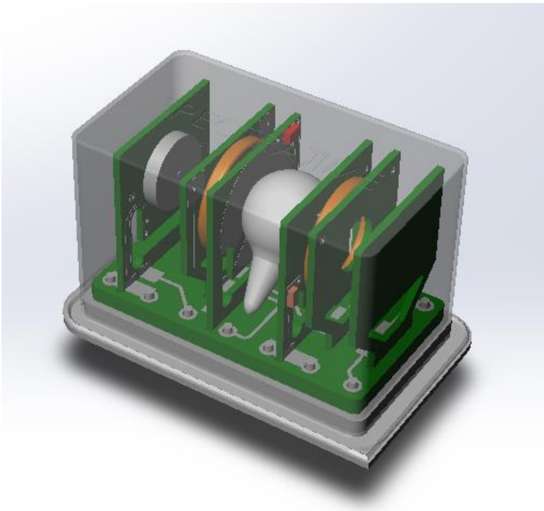


Figure 2.3: Physics package with (optional) DIL-14 package.

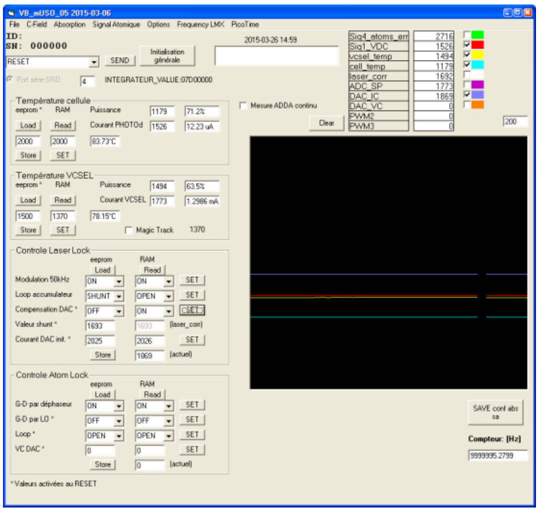


Figure 2.4: Control- and monitoring software for the mTS clock

A software GUI was developed for the control- and monitoring of the mTS clock, see Figure 2.4. Typical control settings include:

11. VCSEL temperature- or current setting (not independent since wavelength fixed at 795 nm)
12. Cell temperature setting
13. C-field current
14. Fractional-N setting (calibration of the clock)
15. Open/close servo-loop (laser and quartz)

Typical telemetry parameters include:

16. Time-stamp, fractional frequency, VCSEL temperature- and current, cell temperature, photo-diode signal, laser-lock error signal, atomic-lock error signal

Besides control- and monitoring, the software is used to scan the laser current to obtain the optical absorption spectrum, or to scan the quartz crystal frequency to obtain the atomic discriminator signal.

2.2 mTS clock performance

Below we give a short summary of the key performance parameters for DUT-01.

Frequency short-term stability and drift: The measured frequency drift at the level of 2E-12/day was well below specification (1E-11/day) as demonstrated in Figure 2.5. The typical short-term frequency stability 1E-10 (at 1 second) in Figure 2.6 was also below specification (2.5E-10).

Power during warm-up and normal operation:
During warm-up the mTS current is limited to 170 mA to protect the transistor heaters. The corresponding power consumption during warmup is 850 mW (+5 Volt regulated supply). The warm-up time (cold start at 25°C) is 4 minutes.

The selected PP design has an average power consumption of 200 mW under vacuum and at -20°C. The electronics package cons umes ~250 mW under the same conditions. The total power consumption of 450 mW (worst case) is a factor of three above specification. While the EP power consumption can be reduced by re-design, the same is not true for the PP. The trade-off between thermal isolation and mechanical stability does not allow to substantially reduce power consumption. A low power PP (<< 200 mW at -20°C) requires the introduction of MEMS technology. The thermal isolation must be designed with MEMS tools – it is not enough to use a MEMS fabricated cell with a “macroscopic” thermal isolation solution.

RF output: Figure 2.7 shows the DUT-01 phase-noise (black line) against the requirements (green line). Since the time-constant for the crystal servo-loop is roughly one second, the measured phase-noise (1 Hz – 100 kHz) is identical to the that of the free-running quartz crystal.

Retrace: Figure 2.8 shows the 24 hours retrace data for DUT-01. When retrace is measured in a stable temperature environment the value is within specification of +/-5E-11. This is the case for DUT-01 (regulated baseplate in vacuum). Otherwise, the retrace is closer to a few +/-1E-10.

Voltage sensitivity: the SMD transistor current rating limits the possibility to run the PP (200 mW) from a +3 Volt supply. Therefore, we choose to operate the PP transistor heaters from a +5V regulation. Figure 2.9 shows frequency sensitivity to supply voltage. Down to +6V (drop-out of 1V) the sensitivity is typically in the range 1E-12/V – 1E-11/V.

Magnetic sensitivity: the inherent magnetic sensitivity of 85Rb (3 GHz) compared to 87Rb (6.8 GHz) is a factor $(6.8/3)^2$ = 5.2 higher. Currently the mTS clock (3 GHz) applies a C-field of 170 mG giving an *inherent* magnetic sensitivity of 1.5E-7/G, i.e. without magnetic shield. In the current mTS configuration, a single layer magnetic shield attenuates this sensitivity to an average of 1.5E-9/G. To reduce this value (which is still a factor x10 above requirement) a second magnetic shield should be inserted around the PP.

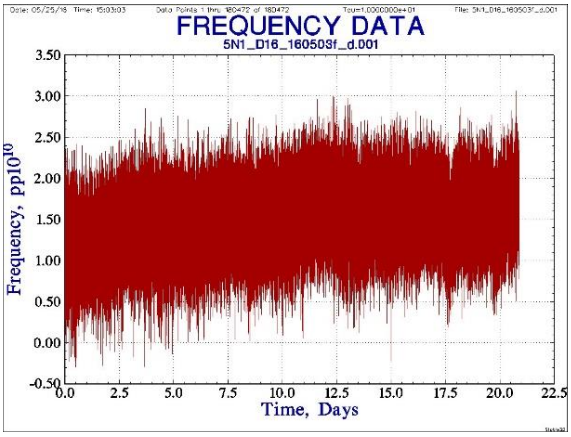


Figure 2.5: frequency data DUT-01 (vacuum, 25°C)

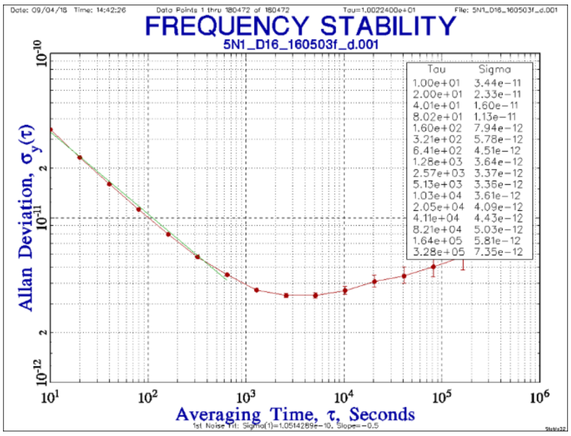


Figure 2.6: ADEV calculated for the data in Figure 2.5.

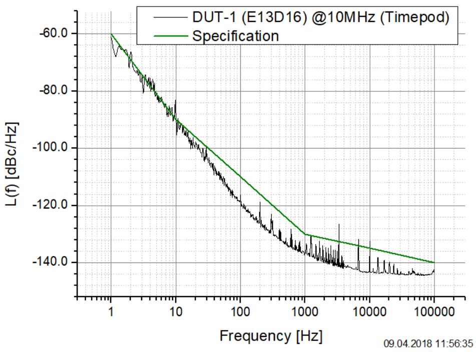


Figure 2.7: DUT-01 phase-noise (black) versus requirement (green)

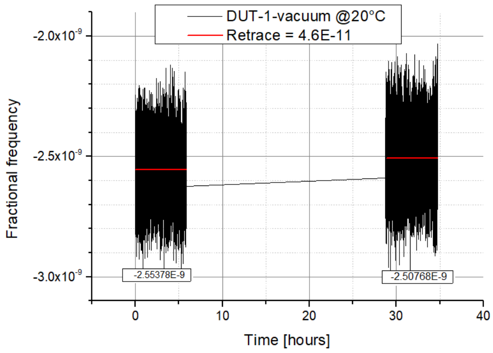


Figure 2.8: DUT-01 retrace (24h, vacuum, 25°C)

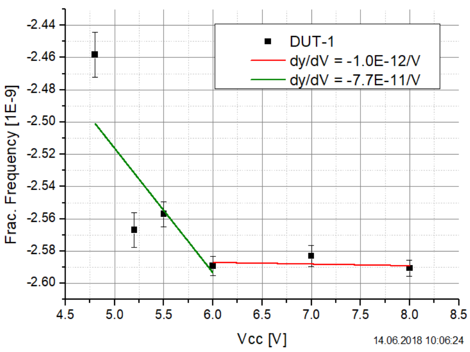


Figure 2.9: DUT-01 voltage sensitivity

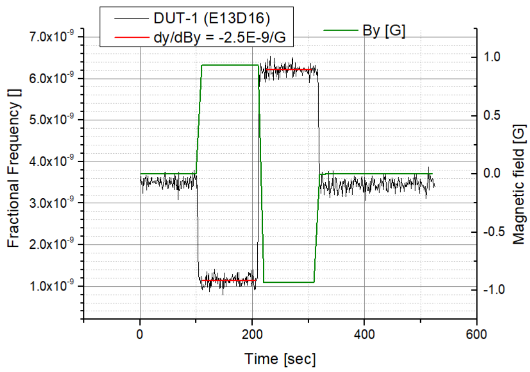


Figure 2.10: DUT-01 magnetic sensitivity

Thermal sensitivity: Figure 2.11 shows the frequency of DUT-01 over a thermal cycle between the temperatures -20°C and 60°C. The frequency variation is Δy = 6.5E-9. The corresponding thermal sensitivity dy/dT = 8E-11/°C is about a factor x10 above specification (< +/-7E-12/°C). Several mitigation solutions to reduce the thermal sensitivity have been identified:

1. Optimize the ratio N2/Ar to reduce the inherent temperature coefficient of the glass cell
2. Stabilize the *monitored* VCSEL current by feedback to the VCSEL temperature
3. Stabilize the *monitored* photo-diode DC-signal by feedback to the CELL temperature
4. Improve the VCSEL current driver
5. Improve the circuit for locking the VCSEL wavelength
6. Compensate frequency changes by C-field adjustment (requires that the frequency varies linearly with temperature over the thermal cycle).

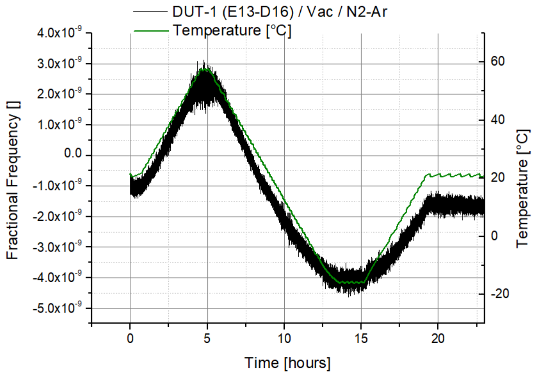


Figure 2.11: DUT-01 Thermal sensitivity

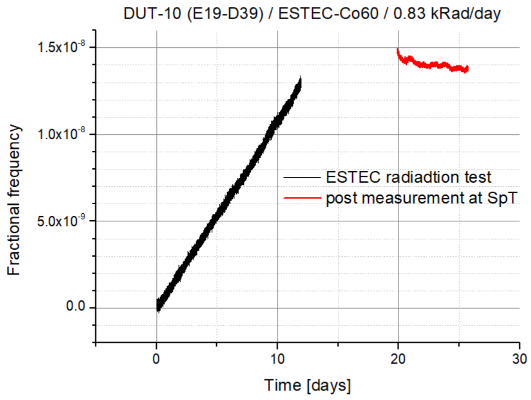


Figure 2.12: DUT-10 radiation sensitivity

Radiation sensitivity: two mTS units (DUT-09 and DUT-10) were tested at the ESTEC Co-60 facility (MeV gamma ray exposure, TID = 10 kRAD). The fractional frequency of each unit was monitored during- and after irradiation, see Figure 2.12. The total frequency shift of 13E-9 corresponds to a radiation sensitivity 1.3E-12/RAD.

The absolute frequency of the PP in DUT-10 (and DUT-11) was measured both before- and after irradiation using a reference EP which was *not* irradiated. This test showed that the PP absolute frequency did not change (within retrace errors). This conclusion was supported by a parallel test where two isolated PP were irradiated with TID = 100 kRAD. Again, comparison showed that the PP absolute frequency measured before- and after the irradiation did not change.

The above observations points towards the EP as the root-cause for the observed frequency shift. For example, the laser lock integrator uses op-amps (LMV358DGK and LMV722) with high voltage offset that are suspected to be sensitive to radiation.

3 Commercial Evaluation

The following table gives a forecast for the addressable market of mTS clocks (= mini Rb) for ground applications.

Mini Rb addressable Market (K units) over 5 years					
Application	**Description**	**Total Market**	**Addressable by Mini RB**	**5-year Forecast**	Remarks
Military Radios	Time sync holdover in TDMA networks for efficient secure operations; GPS recovery	100	10	2.5	Due to lower power consumption ,the miniRb can be used in portable MIL radios . Mass MIL market at ulrta low power cannot be addressed with this version of miniRb
Unmanned Systems	Precise time in UAVs, robots, sensor systems for surveillance	100	20	5	Mini Rubidium have advantages of lowvolume & low mass
Seismic Sensors	Underwater timestamping of sonar data for oil exploration and geological research	10	20	5	Due to very low drift (best in class) the time period between re-synchronisation can be extended to few weeks
Mobile Phone Networks	Synchronization between base stations during GPS outages	100	10	2.5	Depending on price versus alternate solutions such PTP& OCXO
Electric Power Grid	Sync of phasor measurements for realtime control	200	10	2.5	Part of original market of standard Rubidium clocks
Datacenter Sync	large distributed processing for centers like Google, Amazon, Financial Services and Stock Exchanges	100	10	2.5	Part of original market of standard Rubidium clocks
Total		***610***	***80***	***20***	***K units***

A 2017-2026 market report estimates a $100 billion revenue for the LEO segment with 82 percent derived from satellite manufacturing[1]. With many spacecraft manufacturers turning to commercial off-the-shelf (COTS) parts to meet performance, schedule and cost requirements, a commercial space mTS could provide a solution for LEO satellite missions. The mTS space clock applications range from satellite timing and frequency control, to satellite cross linking, and on-board earth observation instruments (e.g. radiometers, radio-occultation).

4 Conclusion and Design Development Plan

The mTS clock shows good frequency performance in terms of short- and long-term stability. Both the ADEV at one second (1E-10) and the frequency drift (2E-12/day) are within requirements. In contrast, the thermal- and magnetic sensitivity need to be improved along with the radiation sensitivity of the electronics package. The clock operating power is at the level of 450 mW (vacuum, -20°C) and 700 mW (PP encapsulated, -20°C). The plan outlined below aims to reduce this power consumption. In the first step the PP power and the PP height will be reduced by using micro-fabrication. In a second step, the EP power consumption will be reduced by using a dedicated ASIC.

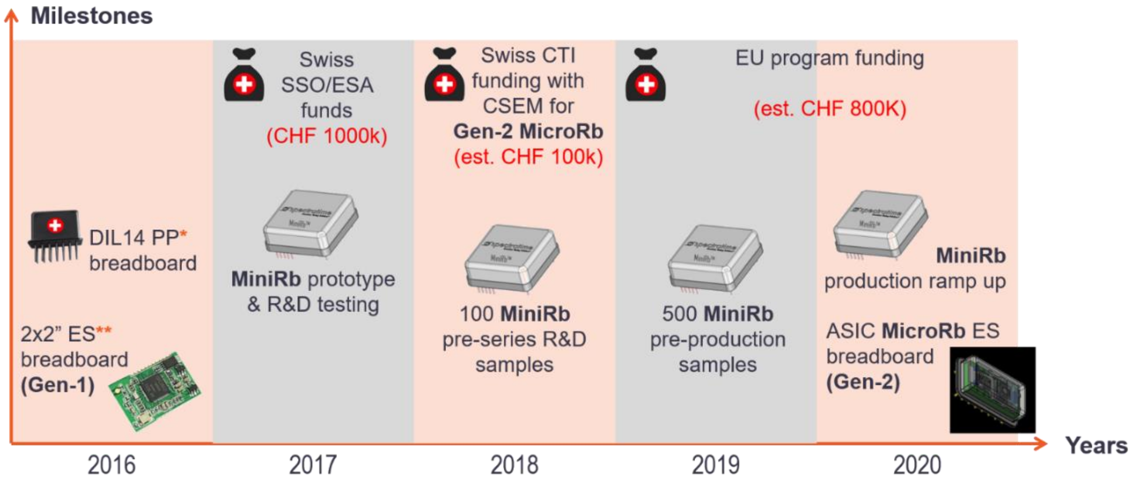
1. Low power physics package: CSEM has developed a low power and low-profile physics package as shown in Figure 4.1. The foot-print (21x15 mm) is comparable to the DIL-14 foot-print used in the mTS clock. However, the height is much lower (5 mm compared to 12.5 mm). The power consumption could be about a factor 3.5 smaller under the same conditions (38 mW compared to 130 mW at 25°C and under vacuum). Since this clock is using MEMs cell, its long-term stability & power consumption versus time is still to be demonstrated.

Therefore, the next steps of the development will be as follows:

[1] Euroconsult, « SATELLITES TO BE BUILT & LAUNCHED BY 2026, World Market Survey”, 2017 Edition

7. Integration of the low power and low-profile PP with the mTS clock electronics using MEM cell and verifications of long term stability and power consumption over time.
8. Trade-off between glass cell or MEMs cell technology (A glass cell could also be used in a lower profile metallic package). Trade-off clock signal interrogation: double-resonance versus CPT.

The roadmap of mTS for the next 3-4 years will be as follows:



Within the end of 2018, we should have a relatively good idea about the long-term stability of the coated MEMs cells within Swiss funding. In any cases, a flat PP will be studied within EU & CTI programs, with or without CPT technique. The final product introduced on the market will still be a 50mm*50mm using various type of physics packages in metallic DIL format. After having selected the best compromise in terms of performances, the electronics could be miniaturized, but only after having produced and delivered several thousands of units to customers.

2. Low power electronics package: In the frame of the mTS project CSEM and SpT defined an ASIC specification file. The ASIC foot-print is 2x2 mm and the total power consumption is expected to be < 30 mW, see Figure 4.2. The clock operating parameters from step 1 will serve to validate and update the ASIC specification file. Therefore, the development and integration of the ASIC naturally follows successful completion of step 1.

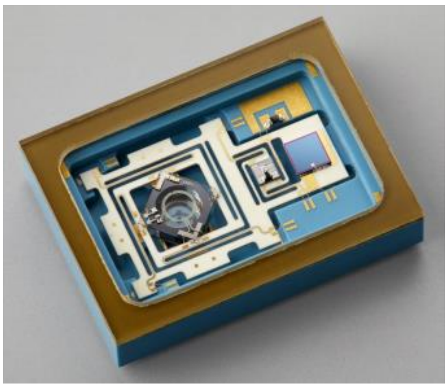


Figure 4.1: Low power and low-profile physics package (21x15x5 mm^3). Source: CSEM.

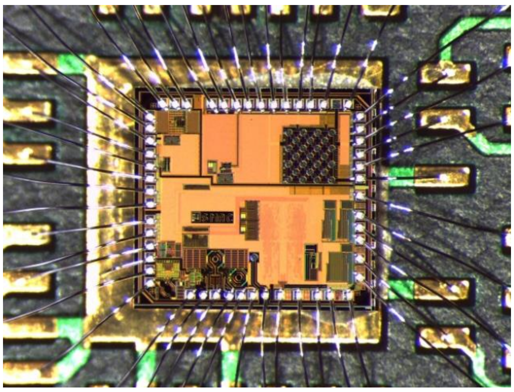


Figure 4.2: CSEM ASIC chip (3.4 GHz) with foot-print 2x2 mm^2