Towards a GNSS-assisted autonomous heterogeneous clock system for very small satellites in the Earth-Moon system

Gill, Eberhard; Palo, Scott

DOI
10.1016/j.actaastro.2025.04.043

Publication date
2025

Document Version
Final published version

Published in
Acta Astronautica

Acta Astronautica 234 (2025) 207–213

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

Towards a GNSS-assisted autonomous heterogeneous clock system for very small satellites in the Earth-Moon system

Eberhard Gill [a,*], Scott Palo [b]

[a] Department of Space Engineering, Delft University of Technology, Kluyverweg 1, 2629 HS, Delft, the Netherlands
[b] Ann & H.J. Smead Department of Aerospace Engineering Sciences, University of Colorado Boulder, United States

ARTICLE INFO

Keywords:
High-stability clock
Small satellite
GNSS
Earth-Moon system
Allan deviation

ABSTRACT

There is an increasing interest in science and exploration missions in the Earth-Moon system. These missions call for simple, efficient and accurate timing onboard of these spacecraft. A heterogeneous onboard timing system is proposed, presented and characterized, which comprises an Oven-Controlled Crystal Oscillator (OCXO) and one or several Chip Scale Atomic Clocks (CSACs), providing nano-second timing accuracy on time scales of seconds to hours. To extend the stability of this system to days, weeks and months, it is assisted by a Global Navigation Satellite Systems (GNSS) timing receiver, which is operated in snapshot mode and activated only for very short time durations of a few seconds on a daily or weekly basis, based on the mission needs. This innovative GNSS assistance replaces the ground-based synchronisation and offers an autonomous operations of the onboard timing system. In this way, a highly accurate yet very low Size, Weight and Power (SWaP) system can be realized, which can be used on very small satellites down to nano-satellites. The onboard architecture of this system is presented and characterised in terms of its achievable Allan deviations as well as its SWaP. It is found that the average power consumption can be as low as 2.2 W, based on a daily GNSS synchronisation schedule, significantly reducing the power requirements over current state-of-the-art solutions. An even less complex variant of this innovative system can be employed for any deep space or planetary mission, replacing the onboard GNSS timing receiver by a traditional time synchronisation mechanism using a terrestrial ground station, or, in the further future, using a pulsar.

1. Introduction

The Earth-Moon system is the target of an increasing number of missions and exploration efforts. Examples of missions are CAPSTONE (Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment), where a 12U CubeSat tests navigation and operations in Near Rectilinear Halo Orbit (NRHO) [Thomson et al., 2022] or various mission studies on ultra-long wavelength radio astronomy using distributed miniaturized satellites in a lunar orbit or a Lagrange point [1]. The Artemis program [2] is a robotic and human Moon exploration program led by the United States' National Aeronautics and Space Administration (NASA) along with six major partner agencies: the European Space Agency (ESA), the German Aerospace Center (DLR), the Japan Aerospace Exploration Agency (JAXA), the Canadian Space Agency (CSA), the Israel Space Agency (ISA), and the Italian Space Agency (ASI). All these missions and activities will require onboard timing information to various levels of accuracy, availability and constraints, depending on the mission needs. Although efforts to establish, as part of Artemis, a lunar communications and navigation architecture called LunaNet [3], its implementation is still to come and the system may also not suit all potential users. An example of the availability and accuracy of Lunar Navigation Services is provided in Ref. [4]. Thus, there is a need for enabling simple, efficient, autonomous and accurate timing onboard of vehicles in the Earth-Moon system. This paper intends to contribute to this need.

A general overview of autonomous cislunar navigation methods is provided in Ref. [5]. Here, and in the present paper, the term cislunar refers to the regime between the Earth and the Moon or the Moon's orbit. However, the particular overview in Ref. [5] is not tailored to timing and does not account for advancements in infrastructure, such as the multi-constellation Global Navigation Satellite Systems (GNSS), or technology, such as the advent of Chip Scale Atomic Clocks (CSACs). For

This article is part of a special issue entitled: 2024 75th IAC Milan published in Acta Astronautica.

* Corresponding author.
E-mail addresses: e.k.a.gill@tudelft.nl (E. Gill), scott.palo@colorado.edu (S. Palo).

https://doi.org/10.1016/j.actaastro.2025.04.043
Received 2 January 2025; Received in revised form 31 March 2025; Accepted 22 April 2025
Available online 5 May 2025
0094-5765/

applications in Low-Earth Orbit (LEO), a high-stability heterogenous clock system onboard small satellites had been proposed [6], comprising a crystal oscillator (XO), one or several CSACs and a GNSS receiver which lead to a system that consumes a total of 3.85 W. A heterogenous clock system, comprising various clock technologies, is particularly interesting as it can cover high temporal stability over a wide range of time periods. Such a system can, however, not be used for cislunar applications, due to challenges of using GNSS with traditional space-capable receivers in these regions. A feasibility study of using GNSS as a navigation system for cislunar applications was conducted by Ref. [7] which showed that although the User Equivalent Range Error (UERE) for GNSS based navigation in cislunar regions is less than 2 m, the Geometric Dilution Of Precision (GDOP) is in the range of 400, leading to high navigation errors $\sigma_r \sim$ UERE*GDOP $\sim$ 700 m. They conclude that GNSS signals can be tracked on the Moon's surface but not with the current GNSS receiver technology for terrestrial use. The usage of GNSS signals for an autonomous navigation system for NASA's planned Lunar Gateway has been addressed in Ref. [8]. An actual technology demonstration of receiving GNSS signals for position, navigation, and timing (PNT) at the Moon has been achieved by the NASA-ASI Lunar GNSS Receiver Experiment (LuGRE) on the Firefly Blue Ghost Mission 1 (BGM1), which uses two Quascom QN400-Space receivers, each with a mass of 1.24 kg and max. operating power of 14 W [9] with a total payload mass of higher than 6.5 kg. However, this mission does not have the goal of establishing a clock system for a broad range of stability timeframes ranging from seconds over hours to weeks.

The objective of this paper is to propose and characterize an onboard clock system which can enable simple, efficient, autonomous and accurate timing in cislunar space. The system shall cover a wide range of stability timeframes from seconds to weeks, suitable for science as well as for exploration applications. The system shall also be characterized by low Size, Weight, Power and Cost (SWaP-C), such that it can fit on very small satellites or rovers. The system may serve different purposes and face different constraints than provided by LunaNet.

This paper will propose a clock system which will develop the concept introduced in Ref. [6] further by simplifying the system, by making it autonomous in cislunar operations and by reducing the SWaP values by a factor of about 2. To this end, the Allan deviations of three clock characteristics, XO, CSAC and GNSS, will be investigated to select a clock subset, which will satisfy a broad range of user needs and fit to the imposed SWaP constraints.

The concept and performance of the system will be introduced in Section 2, including a sensitivity analysis with respect to various types of XOs and number of CSACs. Section 3 will present the architecture of the system and its SWaP characteristics. Section 4 will critically discuss opportunities and challenges of the proposed system, followed by the conclusions provided in Section 5.

2. Concept and performance

The design of a highly stable clock system onboard a very small satellite is based on requirements of the user and mission needs as well as constraints. Of particular relevance is the level of accuracy required and the time interval over which the time stability is desired. In addition, there may be massive constraints in terms of SWaP, especially, if we consider such a system to be used on nano- (masses 1–10 kg), pico- (masses 0.1–1 kg), or even femto-satellites (masses <0.1 kg). While nano- and pico-satellites are well-established for LEO missions, their usage in cislunar space, for planetary missions or deep space missions is just developing [11]. There are various potential clock technologies available for use beyond LEO.

As an example of scientific requirements on clock accuracy, we consider ultra-long wavelength radio astronomy using distributed miniaturized satellites in a lunar orbit or at a Lagrange point [10]. The clock stability is a function of the averaging time, or coherence time, which typically is larger than 1 s. It is often characterized by the Allan deviation [12]. Fig. 1 shows Allan deviations for various clock frequencies as a function of coherence time, based on measurement errors equivalent to one radian. It also shows the particular requirements for a specific radio astronomy application.

2.1. Concept

In this study, we use single-crystal oscillators (XO) and Chip Scale Atomic Clocks (CSACs) as the baseline. Short-term stability is provided by an XO, which could be, following [6], the Evacuated Miniature Crystal Oscillator (EMXO) EX-421 of MicroSemi and the Oven Controlled Crystal Oscillator (OCXO) OX-174, also of MicroSemi. In addition, to assure mid-term stability of the clock system, the MicroSemi CSAC SA.45 is used. The long-term stability of the clock system, if needed, could be realized through terrestrial synchronisation. However, here we assume that GNSS-based synchronisation will be possible in cis-lunar space or using pulsar signals for deep-space missions to realize an autonomous system, although the latter currently requires high SWaP numbers.

The possible components of a heterogeneous clock system are listed in Table 1 with their characteristic stability regime, Allan deviations, and the required power for a specific unit.

2.2. Performance

Once individual clock components have been characterized, the combined Allan deviations can be constructed. They have been computed based on the data provided in Fig. 2 via interpolation of data from each individual component. At first, combinations of two components only are addressed. They are depicted in Fig. 3, where the combination of EMXO and GNSS has been omitted, since it does not provide reasonable stability at mid-term time intervals.

It is obvious that for short coherence times, the Allan deviation of CSAC, EMXO and OCXO, respectively, are most crucial. For longer coherence times, the combinations would be influenced the most by either CSAC or GNSS. Looking at the individual combinations specifically, the OCXO – CSAC combination provides a stable performance slightly above 10^{-12} for time scales of 1–10,000 s, deteriorating for larger coherence times due to the absence of GNSS synchronisation. In contrast, the EMXO – CSAC combination has an inferior performance especially at shorter time scales, only improved by about 14 % as compared to a single EMXO clock through the addition of CSAC. So, in general, if the power constraints are not extremely tight, the OCXO-CSAC combination is preferred to the EMXO-CSAC combination. For the specific radio science application, shown in Fig. 1, such a system could support measurements in the range of 1–180 s, while measurements over a longer interval up to the requested 1000 s would not be possible, not even when using GNSS.

For time spans above about 1 h, Allan deviations below 10^{-12} are no

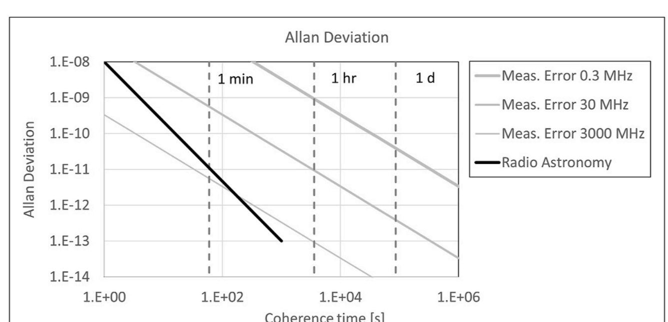

Fig. 1. Allan deviations of phase measurement errors for various frequencies and the scientific requirement from a specific radio astronomy application (Relations and data from Ref. [10]).

Table 1
Options of clock components for autonomous heterogeneous clock system for cislunar missions (data from Ref. [13,14]). Note: Suitability and availability of COTS components require verification.

Component	Stability regime	Allan Deviation	Power [W]	Unit
EMXO	Seconds	$2{\cdot}10^{-11}$	0.25	EX-42
OXCO	Minutes	$3{\cdot}10^{-12}$	1.8	OX-174
CSAC	Hours	10^{-10}-10^{-12}	0.12	SA.45
GNSS	Days	10^{-11}-10^{-13}	1.8	OEM719
Pulsar	Years	$<10^{-9}$	>10	n.a.

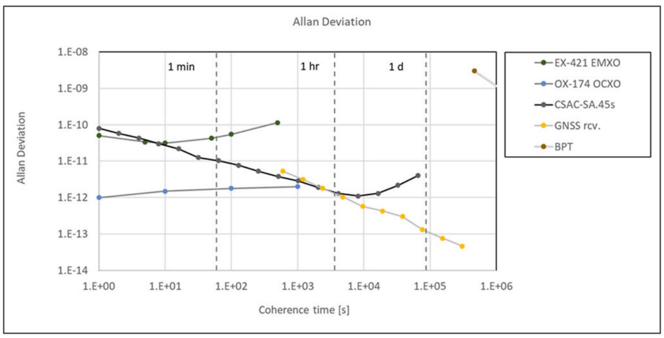

Fig. 2. Allan deviation for various clock components as a function of coherence time (data taken from Ref. [13,15,16]). BPT stands for Binary Pulsar Timing.

longer possible with XO or CSAC, but require synchronisation either from ground or GNSS or, in the future, systems such as LunaNet. This will be detailed in Section 2.3. Again, if low stability is acceptable, CSAC and GNSS could be a solution. However, a superior approach would be the combination of OCXO and GNSS with a maximum Allan deviation of $2.2{\cdot}10^{-12}$ over the entire regime of coherence times of 1 s–3 d and far beyond.

If we consider an even more complex heterogenous clock system which consists of three different elements, it is obvious that GNSS must be part of it. Thus, we are left with the combinations of either EMXO-CSAC-GNSS or OCXO-CSAC-GNSS which are both depicted in Fig. 4 in terms of their Allan deviation.

The superior system is obviously the combination of OCXO-CSAC-GNSS. It has Allan deviations of less than $1.25{\cdot}10^{-12}$ over the entire coherence time intervals of 1 s–1 d and beyond. However, the performance of such system in terms of Allan deviation is improved through the addition of a CSAC by only 4 %.

As van Buren [van Buren et al., 2022] has pointed out, additional identical CSACs would statistically improve the overall performance by sqrt(N), N being the number of CSACs. Having more than one CSAC might not only be preferred in terms of redundancy, but also has a moderate power penalty, as a single CSAC only requires ~0.12 W. The impact of adding CSACs to a combined OCXO – CSAC system is depicted in Fig. 5. It is obvious that the impact is only visible at mid-term time intervals, where again GNSS would come in as a significant improvement. Thus, the benefit of several CSACs is limited in terms of improved performance.

2.3. Synchronisation using GNSS

The above system provides stability of about 10^{-12} for time spans of 1–10^4 s according to Fig. 3. However, if a stability over longer times at a high accuracy is needed, additional time synchronisation measures will be necessary. Traditionally, this is done using ground-based time synchronisation with a terrestrial ground station which is equipped with an atomic clock reference. The achievable time synchronisation error δt is given by $\delta t \approx \delta r/c + \delta t_A$ where δr is the position error of the satellite along the link, c is the velocity of light and δt_A is the impact of the

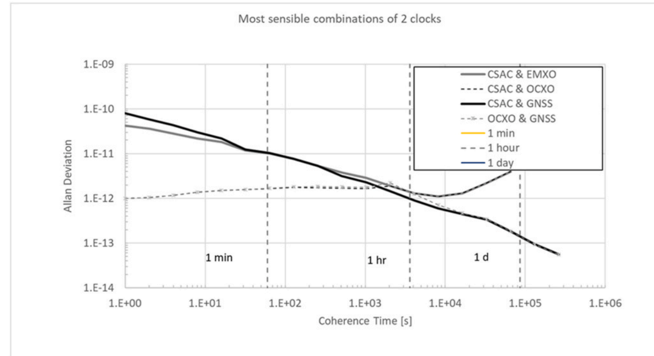

Fig. 3. Allan deviations for selected 2-component heterogenous clock systems as a function of coherence time.

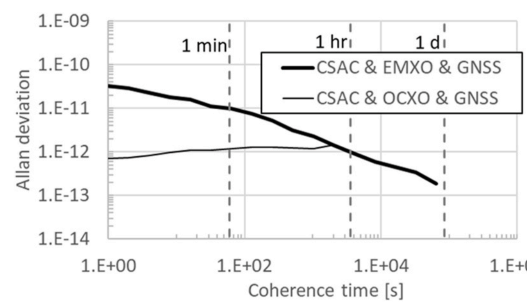

Fig. 4. Allan deviations for selected 3-component heterogenous clock systems as a function of coherence time.

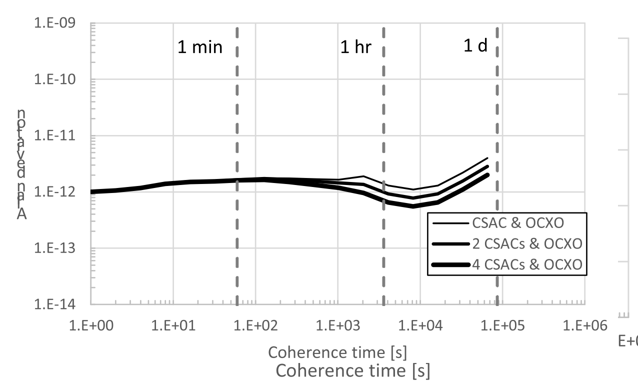

Fig. 5. Allan deviations for the CSAC – OCXO system with various CSAC units.

atmosphere on the signal propagation. However, ground-based synchronisation involves costly operations of ground stations and essentially makes the system non-autonomous.

In contrast, at least in principle, the onboard clock system could be synchronized using a spaceborne GNSS timing receiver, or a general GNSS tracking receiver, that is assisted with a priori known position information from the navigation system. In this case, the GNSS-assisted clock system would need to be synchronized only every few hours, taking into account proper weighting factors, treatment of process noise and depending on the specific mission needs. This would render the clock system independent from ground operations, thus making it autonomous. In this scenario, the GNSS receiver would need to be activated only for short time spans and basically be operated as a snapshot receiver. In contrast to traditional GNSS receivers, snapshot receivers sleep for most of the time and wake up at defined intervals to record short snapshots of GNSS signals [17]. Obviously, while activation of the receiver could be done in an automated way, power consumption will increase with the frequency of activation. These receivers digitize the raw signals and store them locally, while the processing of these signals and the estimation algorithms is done on a separate processor. Interestingly, while using snapshot receivers for cis-lunar missions has to the best knowledge of the authors not been proposed before, it already has been demonstrated for weak signal conditions in Geosynchronous Transfer Orbit (GTO) as early as 1997 [18]. *The challenge of precise timing using the GNSS snapshot principle has been addressed in [Roy* et al. *2021].*

For the Moon, the necessary minimum sample integration time has been determined for the LuGRE project [Parker et al., 2022, [19] which is depicted in Figs. 6 and 7. *As can be seen from* Fig. 6*, lower signal values increase the required sampling time. Using the full search space obviously requires the highest sampling time. The sampling time may be reduced by reducing the Doppler bins at the expense of accuracy. For LuGRE, the authors conclude (*cf. Fig. 7*) that 300–*400 ms *of snapshot duration would be enough to track at least one satellite in most cases* [19]. *For a miniaturized GNSS timing system, further investigations would be necessary, which is beyond the scope of this paper.*

*Signal acquisition in cislunar space has been reported on March 5*th, *2025* [20].*Parker* [Parker et al., 2022] described the GNSS system for operations on the lunar surface where the receiver requirements foresee a weak signal acquisition and tracking threshold of <23 dB-Hz. Conditions in cislunar space, in particular at the Lagrange points, would differ from these specifications. The relative signal levels at the Lagrange points as compared to the Earth-Moon distance are provided in Table 2. These values may vary by up to about ±0.7 dB due to the distances of the GNSS satellites with respect to the center of the Earth.

For systems beyond cislunar distances, GNSS would no longer be an option. If stability and synchronisation would be aimed in a fully autonomous way over a very long time span, the use of pulsars could become an option [14]. *The feasibility of frequency steering of an onboard clock using the Crab pulsar has been demonstrated onboard the XPNAV-1 satellite in LEO* [21]. *However, the system complexity and SWaP characteristics of such a pulsar-assisted OCXO-CSAC clock system would certainly grow tremendously in comparison to a two-component clock system.*

3. Architecture & characteristics

Once the components of the clock system have been identified and the performance characteristics have been determined, we can sketch the architecture of the system and establish key SWaP parameters.

3.1. Architecture

A simple architecture of a CSAC-disciplined OXCO clock system is shown in Fig. 8. The algorithms are executed on a processor which could be part of the onboard computer (OBC) or a dedicated Field-programmable gate array (FPGA), as proposed in van Buren [6]. The processor would receive the signals from the CSAC and OCXO and a 10

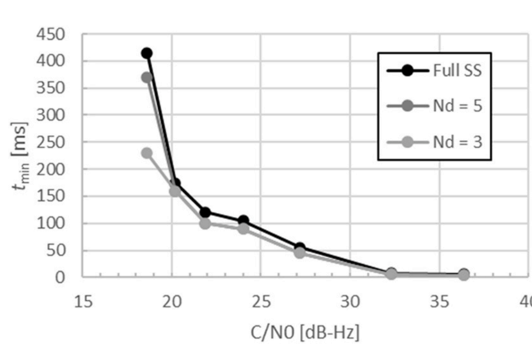

Fig. 6. Minimum sample integration time of GNSS signal as a function of the Carrier to Noise (C/N) ratio. SS denotes Search Space and Nd denotes number of Doppler bins. Values taken from [Parker et al., 2022].

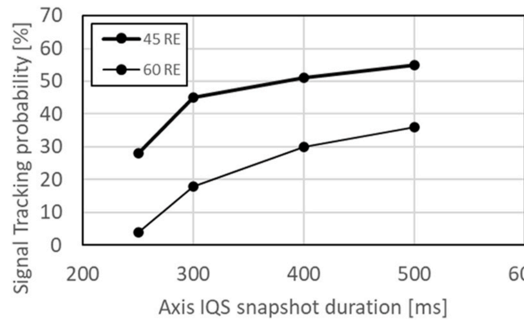

Fig. 7. Probability for tracking GNSS signals w.r.t. I-Q samples (IQS), parametrized with Spacecraft-Earth distances in units of Earth radius (RE). Values taken from Ref. [19].

Table 2
Signal strength ratios of Lagrange points (L) in the Earth - Moon (EM) system.

Component	Distance [km]	Signal Ratio [dB]
E-M	384400	0.00
E-L1	323050	−1.51
E-L2	445747	1.29
E-L3	381665	−0.06
E-L4/5	384400	0.00

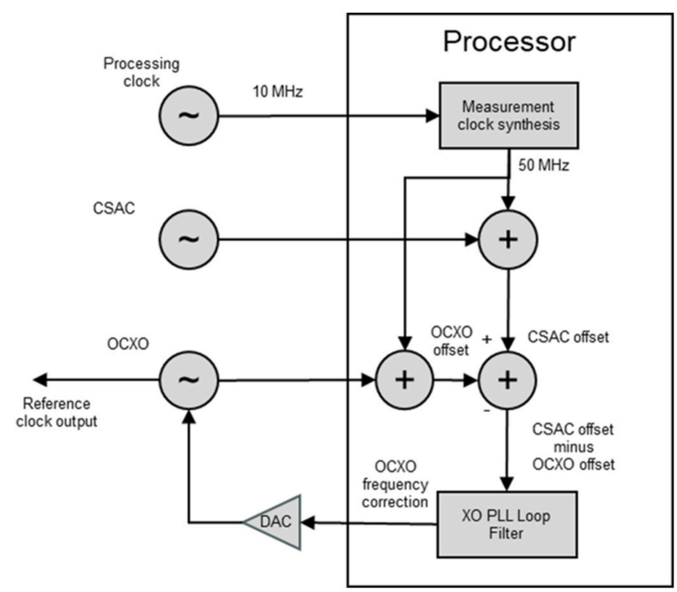

Fig. 8. Architecture of a CSAC-disciplined OCXO clock system (inspired by [van Buren et al., 2021]).

MHz Complementary Metal-Oxide-Semiconductor (CMOS) processing clock. The latter is used to synthesize a measurement clock at a frequency close to 50 MHz, as described by van Buren [6]. This clock is then used to generate the offsets to CSAC and OCXO, which are combined and fed into a Phase Lock Loop (PLL), which converts the time errors into a frequency correction which is again fed back to the OCXO via a Digital to Analog Converter (DAC). The OCXO finally outputs the reference clock of the system. Such CSAC-disciplined OCXO could be used for applications, such as deep space or planetary missions, where no GNSS is available and long-term synchronisation would rely on the ground segment.

For missions in the cislunar regime where GNSS could be available, a more complicated system is proposed, where GNSS signals would be used once every few hours or days, as explained above, to provide long-term stability of the clock system. Such architecture is shown in Fig. 9. The GNSS receiver may be assisted with position and velocity (PV) information, e.g. from an onboard navigation system (ONS) to simplify the acquisition process and improve the accuracy of the time solution, shown by the dashed line in Fig. 9. The sequence of time offset determination is to first compute the GNSS and CSAC time offsets and subsequently determine the offset of OCXO w.r.t. the GNSS and CSAC time offsets. In addition, relativistic corrections need to be applied to account for the fact that GNSS refers to the relativistic effects in an Earth-centered system.

3.2. Characteristics

For very small satellites, out of the three parameters in the SWaP characteristics, power consumption is the most serious constraint, as size and mass of the key elements of such a system are basically at chip-size level. The power constraint is even more severe for missions in cislunar, planetary or deep space missions than in LEO.

In Table 3, the estimated average power consumption is shown for both the CSAC-disciplined OCXO system as well as for the GNSS-assisted CSAC-disciplined OCXO system. We also show the power requirements for continuous GNSS receiver operations. We assume a constant processor power of 0.25 W and a GNSS receiver power in continuous operation of 1.8 W, typical for the Novatel OEM-719 receiver. The sampling period of the GNSS receiver is assumed to be 1 s. A passive GNSS antenna is assumed.

The snapshot operations of the GNSS receiver thus saves at least 45 % of the total power consumption for a continuous operations. Thus, a total average power consumption of about 2.2 W is necessary to support *the proposed clock system. As compared to the OCXO system proposed in van Buren* [van Buren et al., 2021], which requires 3.85 W, the presented system provides, due to the snapshot operations, a power reduction of 45 %.

While a power consumption of 2.18 W for a precise clock system on board of a small satellite would definitely not be realistic for a femto-satellite and be challenging for a pico-satellite, it is definitely suitable for nano-satellites and certainly for all types of micro-satellites.

4. Opportunities & challenges

This section provides a critical analysis on the opportunities and challenges associated with the proposed clock system.

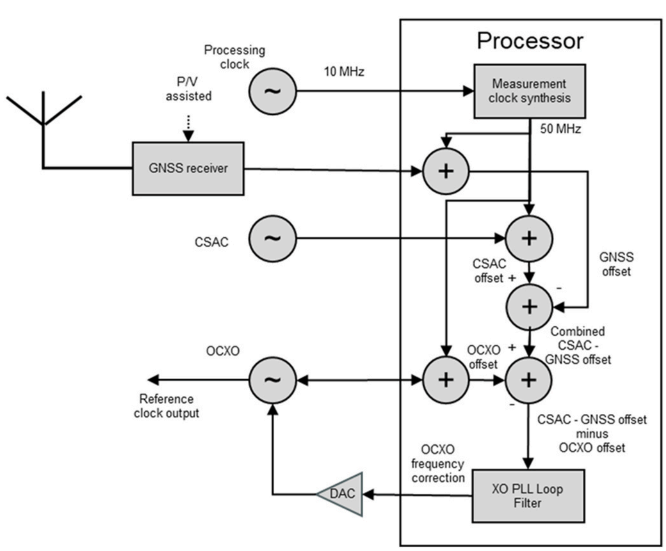

Fig. 9. Architecture showing a CSAC-disciplined OCXO clock system assisted by GNSS synchronisation (inspired by [van Buren et al., 2021]).

Table 3
Average system power requirements for various clock system configurations.

Configuration	Power [W]
CSAC-disciplined OCXO	2.180
GNSS-ass. CSAC-disc. OCXO (cont.)	3.980
GNSS-ass. CSAC-disc. OCXO (1/hr)	2.181
GNSS-ass. CSAC-disc. OCXO (1/d)	2.180

4.1. Opportunities

There are two key areas, where the proposed system holds key opportunities: applications and technology. In the area of applications, autonomy and the spatial regime of usage are the prominent ones. In terms of technology, the development of new clock-related concepts as well as miniaturisation and integration play key roles.

While previous systems on small satellites in orbits beyond LEO were dependent on the time synchronisation from terrestrial ground support, the use of GNSS in cislunar space, although still in exploration phase, provides the opportunity to reduce costly ground operations, at least for the timing system, and thus offer a new level of autonomy. This opportunity is not limited to cost savings only, but can be seen as enabler for complex spacecraft operations, which would need to exclude signal-round trip times between the Earth and the lunar vicinity.

Second to autonomy, the usage of the proposed system beyond LEO and in particular in cislunar space opens up a new orbital regime which tries to exploit the GNSS Space Service Volume (SSV) [22]. This may play an important role prior to and during the installation of LunaNet. The fact that GNSS reception experiments at lunar distance has been (Schauer 2025) and will be conducted in the near future [19] offers the chance to increase their technology readiness levels (TRL). For scientific purposes requiring short-term clock stability, the system may also be used in planetary missions or for deep space probes, where only limited absolute timing information is necessary. Also, it enables one-way crosslink operations, e.g., one-way forward-ranging between satellites at Earth-Moon Lagrangian orbits, allowing more navigation data to be collected.

In the area of technology, new clock concepts or advanced clock models may become available. An example of a new clock concept is the atomic beam clock [23]. Although currently not competitive to CSACs, it may have high potential in the future. In addition, the trends for miniaturisation offer the opportunity to decrease the SWaP further, allowing the usage of the proposed system on pico- or even femto-satellites. For an entire clock system, not only the individual components play an important role, but also how these components are integrated. A tighter integration as well as an increased use of Commercial off-the-shelf (COTS) products will contribute to high functionality while further reducing SWaP and cost.

4.2. Challenges

There are two key areas, which are considered to provide the largest challenges to the clock system proposed herein. One challenge is the GNSS acquisition and operations, the other challenge is the environmental conditions in the cislunar regime or deep space, in particular the thermal stability.

The challenge of GNSS acquisition and operations has various aspects. First and utmost, it is the challenge of signal acquisition itself. The very weak GNSS signals in cislunar space will have an impact on the clock system, e.g. the selected GNSS receiver, the Low-Noise-Amplifier (LNA) and the antenna. The technology demonstration payload on LuGRE, tailored to specifically demonstrate GNSS reception at the Moon, has high SWaP values of 14 W and 5 kg [Parker et al., 2022], about one order of magnitude higher than the system proposed here, and e.g. employs a high-gain antenna. It is expected that a massive drop in

SWaP values can be expected once the concept has successfully been demonstrated, technology has been adapted and optimized based on the gained experience and small satellite missions will be defined which allow for a higher risk level. Next, the operations of a GNSS receiver as a time synchronisation device may face the challenge to find companies, willing to produce and deliver these products. Also, the operations of such receiver in a snapshot mode is unconventional. However, the fact that the receiver would, if properly assisted by external position and velocity information, only have to acquire one of the many GNSS satellites to decode its signal and derive the GNSS time, is a prospect in itself which may ease its usage.

Second, the thermal and radiation environment could represent a challenge to the proposed clock system especially on small satellites with very limited power resources. The impact of temperature variations on Cubesats in LEO has been analysed in Ref. [24]. However, the temperature gradients for missions in transfer orbits in cislunar space will be significantly smaller than for LEO missions. For satellites on Low Lunar orbits (LLO), the orbital periods are similar to LEO and thus will be the temperature gradients. Temperature induced sensitivities on CSACs have been studied by van Buren [13]. The fact that the proposed system relies on an OCXO, rather than an EMXO, however, assures that thermal gradients have already been confined by design, although at the price of a higher power consumption.

Related to and beyond those two key challenges, there are certainly many other specific problems, such as proper antenna pointing, which need to be solved and are expected to be treated in future research.

5. Conclusions

A highly miniatured autonomous and heterogeneous clock system for very small satellites in cislunar, planetary or deep space orbits has been proposed and characterised. It comprises of an OCXO for short-term and a CSAC for mid-term clock stability. This two-component system uses less than 2.2 W to provide Allan deviations of better than $2.2\cdot10^{-12}$ for time scales in the range of 1 s–4 h. If also long-term stability is required, the innovative use of a GNSS receiver in snapshot mode is proposed in cislunar orbits which effectively does not increase the power consumption and maintains the autonomy of the system. Such a GNSS-assisted combined OCXO-CSAC system would have its maximum Allan deviation of $1.45\cdot10^{-12}$ at around 30 min, while the short-term stability at 1 s would be $7\cdot10^{-13}$ and its long-term stability would be $6\cdot10^{-14}$ at 3 d, governed by GNSS. While the two-component system can be used on any nano-satellites or micro-satellites, the three-component system still requires efforts to increase its Technology Readiness Level. At the same time, it holds prospects for further research and enhanced applications.

CRediT authorship contribution statement

Eberhard Gill: Writing – original draft, Software, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Scott Palo:** Writing – review & editing, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

[25,26]

Acknowledgements

The research leading to this publication has to a great extent been performed by the first author as part of the 2023 Byram Distinguished Visiting Professorship at the Ann and H.J. Smead Department of Aerospace Engineering Sciences at the University of Colorado, Boulder, CO, USA. He is grateful to all faculty of the department, enabling and supporting his research stay and for the hospitality, he experienced. Erdem Turan, PhD candidate at Delft University of Technology, has provided a valuable review of the manuscript.

References

[1] R.T. Rajan, A.J. Boonstra, M. Bentum, M. Klein-Wolt, F. Belien, M. Arts, N. Saks, A. J. van der Veen, Space-based aperture array for ultra-long wavelength radio astronomy, Exp. Astron. 41 (2016) 271–306.

[2] M. Smith, D. Craig, N. Herrmann, E. Mahoney, J. Krezel, N. McIntyre, K. Goodliff, The Artemis Program: an Overview of NASA's Activities to Return Humans to the Moon, IEEE Aerospace Conference, Big Sky, MT, USA, 2020, 7-14 March.

[3] J. Israel, K.D. Mauldin, C.J. Roberts, J.W. Mitchell, A.A. Pulkkinen, L.V.D. Cooper, M.A. Johnson, S.D. Christe, C.J. Gramling, LunaNet: a Flexible and extensible lunar exploration communications and navigation infrastructure, in: 2020 IEEE Aerospace Conference, Big Sky, MT, USA, 2020, 7-14 March.

[4] R. Kapoor, R. Sabatini, A. Gardi, Analysis of small satellite-based lunar navigation Service availability and accuracy on the surface and in low orbit, Lublin, Poland, in: 2024 IEEE International Workshop on Metrology for AeroSpace, MetroAeroSpace 2024, 2024, 3-5 June.

[5] J.A. Christian, E.G. Lightsey, Review of options for autonomous cislunar navigation, J. Spacecraft Rockets 46 (2009) 1023–1036.

[6] D. Van Buren, P. Axelrad, S. Palo, Design of a high-stability heterogeneous clock system for small satellites in LEO, GNSS Solutions 25 (2021).

[7] V. Capuano, C. Botteron, J. Leclère, J. Tian, Y. Wang, P.A. Farine, Feasibility study of GNSS as navigation system to reach the Moon, Acta Astronaut. 116 (2015) 186–201.

[8] L.B. Winternitz, A. William, A. Bamford, A. Long, M.A. Hassouneh, GNSS based autonomous navigation study for the lunar Gateway, 42nd AAS guidance, in: Navigation and Control Conference, Breckenridge, CO, United States of America, 2019, 31 Jan. – 6 Feb.

[9] J.J.K. Parker, F. Dovis, B. Anderson, L. Ansalone, B. Ashman, F.H. Bauer, G. D'Amore, C. Facchinetti, S. Fantinato, G. Impresario, S.A. McKim, E. Miotti, The lunar GNSS receiver experiment (LuGRE), in: Proceedings of the International Technical Meeting of the Institute of Navigation, ITM 2022, Long Beach, U.S.A., 2022, pp. 25–27. January.

[10] R.T. Rajan, M. Bentum, A.-J. Boonstra, Synchronization for space based ultra low frequency interferometry, in: 2013 IEEE Aerospace Conference, Big Sky, MT, USA, 2013, pp. 2–9. March.

[11] A. Freeman, Exploring our solar system with Cubesats and smallsats: a NASA/JPL perspective, 4S Symposium, Sorrento, Italy (2018). **28 May – 1 June**.

[12] D.W. Allan, Time and frequency (Time-Domain) characterization, estimation, and prediction of precision clocks and oscillators, IEEE Trans. Ultrason. Ferroelectrics Freq. Control 34 (1987) 647–654.

[13] D.A. Van Buren, Techniques for precise timing onboard small satellites, PhD thesis University of Colorado, Boulder (2020).

[14] N. Xiaolin, Y. Yuqing, G. Mingzhen, W. Weiren, F. Jiancheng, L. Gang, Pulsar navigation using time of arrival (TOA) and time differential TOA (TDTOA), Acta Astronaut. 142 (2018) 57–63.

[15] R. Lutwak, S.A. The, 45s chip-scale atomic clock – early production statistics, 43rd Annual Precise Time and Time Interval Systems and Applications Meeting, Long Beach, California, USA. November 14–17 (2011) 207–220.

[16] M.A. Lombardi, L.M. Nelson, A.N. Novick, V. Zhang, Time and Frequency Measurements Using the Global Positioning System, 2001.

[17] J. Beuchert, A. Rogers, SnapperGNSS - algorithms for energy-efficient low-cost location estimation using GNSS signal snapshots, Coimbra, Portugal, in: Proceedings of the 19th ACM Conference on Embedded Networked Sensor Systems (SenSys'21), 2021, pp. 15–17. Nov.

[18] T.D. Powell, P.D. Martzen, S.B. Sedlacek, C.C. Chao, R. Silva, A. Brown, G. Belle, GNSS signals in a geosynchronous transfer orbit: "falcon gold" data processing, 1999 National Technical Meeting of The Institute of Navigation, San Diego, CA, United States of America, January (1999) 575–585.

[19] A. Nardin, A. Minetto, S. Guzzi, F. Dovis, L. Konitzer, J. Parker, Snapshot tracking of GNSS signals in space: a case study at lunar distances, in: 36th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2023), October 2023.

[20] K. Schauer, NASA Successfully Acquires GPS Signals on Moon; https://www.nasa.gov/directorates/somd/space-communications-navigation-program/nasa-successfully-acquires-gps-signals-on-moon/, last visited 2025/03/26.

[21] M. Han, M. Tong, L. Li, Y. Shi, T. Yang, Y. Gao, Frequency steering of spaceborne clocks based on XPNAV-1 observations, Chin. J. Aeronaut. 36 (6) (2023) 266–278.

[22] F.H. Bauer, J.K. Parker, B. Welch, W. Enderle, Developing a robust, interoperable GNSS space Service Volume (SSV) for the global space user community, in: ION International Technical Meeting, Monterey, CA, United States of America, 2017, January 30 – February 2, pp. 132–149.

[23] G.D. Martinez, C. Li, A. Staron, J. Kitching, C. Raman, W.R. McGehee, A chip-scale atomic beam clock, Nat. Commun. 14 (2023 Jun 13) 3501.

[24] M. Rybak, P. Axelrad, J. Seubert, Investigation of CSAC driven one-way ranging performance for CubeSat navigation, 32nd Annual AIAA/USU Conference on Small Satellites, Logan, UT, United States of America (2018). **August 4**.

[25] R. Blay, B. Wang, D.M. Akos, Deriving accurate time from assisted GNSS using extended ambiguity resolution, navigation, J. Inst. Navig. 68 (2021) 217–229.

[26] M. Thompson, A. Forsman, B. Peters, T. Ely, D. Sorensen, B. Cheetham, Cislunar Navigation Technology Demonstrations on the CAPSTONE Mission, Institute of Navigation, International Technical Meeting at Long Beach, CA United States of America, 2022, 25-27 Jan.