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Review

A Survey on Atomic Clocks in GNSS and Beyond

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Abstract

Space-based navigation systems rely on atomic clocks aboard satellites to provide precise time and positioning information through synchronized radio-frequency signals. At the core are Atomic Frequency References (AFRs), which stabilize a local oscillator using atomic transitions to achieve exceptional accuracy and stability. To maintain 1 m positioning precision, timing uncertainties below 3 ns are required, achievable only with high-quality atomic clocks. This paper surveys the principles, architectures, and performance of AFRs in satellite navigation, including the types deployed in major Global Navigation Satellite System (GNSS) constellations such as GPS, Galileo, GLONASS, and BeiDou, and discusses current practices and emerging trends in satellite timing technologies, including the nascent Low-Earth-Orbit Positioning, Navigation, and Timing (LEO-PNT) paradigm.

Keywords: atomic clocks; GNSS; LEO-PNT; AFR; hydrogen maser; CSAC; GPS; Galileo; GLONASS; BeiDou

1. Introduction

Atomic clocks represent the pinnacle of chronometric precision, serving as the foundational frequency references for modern timekeeping and navigation infrastructures. Unlike mechanical or quartz-based oscillators, atomic clocks exploit quantum mechanics by stabilising a local oscillator to the ground-state hyperfine transition frequency of an atom—typically an alkali atom such as rubidium-87 (^{87}Rb) or caesium-133 (^{133}Cs). This process involves the interaction between nuclear and electron spins, resulting in a transition frequency that is remarkably stable and largely independent of external perturbations [1]. The necessity for such precision is driven by the physical relationship between time and distance: since electromagnetic signals travel at the speed of light, a timing error as small as three nanoseconds translates to a positioning error of approximately one metre [2]. Consequently, spaceborne AFRs are engineered to achieve fractional frequency instabilities on the order of 10^{-14} over a one-day interval [3,4]. This stability is realised through a frequency-locked loop in which optical pumping and microwave interrogation generate an error signal that continuously steers a precision quartz crystal oscillator to the atomic resonance frequency, thereby keeping the satellite's onboard clock synchronised with the constellation's reference time scale [5].

The global satellite navigation market continues to expand rapidly. According to the EUSPA EO and GNSS Market Report 2024, the downstream GNSS sector generated revenues of approximately EUR 260 billion in 2023 and is forecast to grow to EUR 580 billion by 2033, driven primarily by mass-market applications in smartphones, automotive systems, and precision agriculture [6]. The number of GNSS-enabled devices is projected to reach almost

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9 billion by 2033, with annual shipments rising from 1.6 billion units in 2023 to 2.2 billion by 2033 [6]. This rapid growth sustains demand for a new generation of atomic clocks delivering improved accuracy, integrity, and resilience for GNSS services [6].

GNSS constellations deliver global, autonomous positioning to user equipment without any return link to the satellites, forming the backbone of modern Positioning, Navigation, and Timing (PNT) services. The fundamental concept is based on one-way ranging: a receiver measures the apparent travel time of signals from four or more satellites, derives pseudoranges, and applies trilateration to resolve its three-dimensional coordinates and clock offset relative to the constellation's reference time scale [7]. The GNSS —GPS (United States), GLONASS (Russia), Galileo (European Union), and BeiDou (China)—are each built around a three-segment architecture comprising a space segment of orbiting atomic clocks, a ground control segment responsible for orbit monitoring and clock correction, and a user segment of GNSS receivers [3,4,7]. The metrological anchor for these system time scales is the international ensemble of primary and secondary frequency standards that realise Coordinated Universal Time (UTC), so that improvements in spaceborne and laboratory atomic clocks propagate directly into navigation and timing performance [1,8].

An important emerging complement to MEO-based GNSS is Low-Earth-Orbit PNT (LEO-PNT), in which dedicated navigation payloads in LEO broadcast ranging signals to ground users [2]. LEO satellites at altitudes below 2000 km transmit signals substantially stronger at ground level owing to reduced free-space path loss, and offer a more rapidly changing satellite geometry that reduces time-to-first-fix and improves dilution-of-precision values [9,10]. The integration of Chip-Scale Atomic Clocks (CSACs) into CubeSat-class platforms is making LEO-PNT technically and economically viable [11–13]. This paper also addresses LEO-PNT AFR requirements, with particular attention to the ESA Celeste in-orbit demonstration mission [14,15].

2. Quantum Principles and Accuracy Framework

2.1. Hyperfine Structure and the Clock Transition

The operational principle of every atomic frequency reference (AFR) is the use of an atomic hyperfine transition as an invariant natural constant to regulate a man-made oscillator. Following Hollberg, we distinguish between an Atomic Frequency Reference (AFR)—a device that stabilises a local oscillator to an atomic quantum transition to provide a known, stable output frequency—and an atomic clock, which additionally incorporates a totalising counter referenced to a defined time epoch; the term 'atomic clock' is therefore often used loosely in the literature to refer to what is strictly an AFR [5]. AFRs leverage the ground-state hyperfine energy levels of alkali atoms such as rubidium and caesium, and of atomic hydrogen. The $\Delta m_F = 0$ clock transition is selected because it is first-order independent of external magnetic fields by symmetry; the residual field sensitivity enters only at second order via the quadratic Zeeman effect, which is characterised and controlled as part of the systematic error budget [1,5]. For ^{87}Rb the clock transition is the ground-state hyperfine splitting between the F = 2, $m_F = 0$ and F = 1, $m_F = 0$ sublevels of the $5S_{1/2}$ state, at 6.8346826109043 GHz; for ^{133}Cs the analogous transition between the F = 4, $m_F = 0$ and F = 3, $m_F = 0$ sublevels of the $6S_{1/2}$ state defines the SI second at exactly 9,192,631,770 Hz; and for atomic hydrogen the F = 1 $\rightarrow$ F = 0 ground-state transition is at 1.420405751 GHz [1,5].

To interrogate the clock transition, a non-equilibrium population difference between the two hyperfine ground-state levels must first be established. In lamp-pumped rubidium standards, optical pumping is accomplished by illuminating the atomic vapour with light from a spectral lamp, which preferentially removes atoms from one hyperfine level through photon absorption and spontaneous emission. In laser-pumped and chip-scale clocks, the same function is served by narrow-linewidth diode lasers or modulated

vertical-cavity surface-emitting lasers (VCSELs) [11]. The resulting population imbalance is a prerequisite for detecting the microwave-induced clock transition by monitoring the change in transmitted light through the cell [1,5].

2.2. Architecture of a Frequency-Locked Loop

The architecture of an AFR is built upon electronic signal generation and quantum interrogation. At its foundation is a high-stability Local Oscillator (LO), typically a precision quartz crystal, which provides a clean but inherently drifting output frequency. A frequency synthesiser scales and modulates the LO's output until it matches the hyperfine transition frequency of the chosen atomic species. This synthesised signal is then injected into the Physics Package, the core component where the physical interaction with atoms occurs. The Physics Package contains the atomic medium—typically as a high-temperature vapour in a glass cell or as a collimated beam—housed within a microwave cavity designed to maximise the electromagnetic coupling between the synthesised field and the atoms. The cavity environment is precisely controlled, utilising multi-layer magnetic shielding to attenuate external interference and precision heaters to maintain a stable atomic density, ensuring that the atoms are correctly prepared for state interrogation via optical or microwave techniques [1,5].

The conversion of the physical interaction into a stable timekeeping reference is managed by a high-gain feedback control system. As the synthesised microwave signal sweeps across the atomic resonance, a detection sensor—usually a photodetector—monitors the change in the atoms' energy state by measuring the intensity of light transmitted through the medium. This optical signal reveals a characteristic absorption dip or peak at the exact moment of quantum resonance, which the feedback electronics use to derive a precise error signal. By continuously adjusting the LO's control voltage, the loop locks the oscillator to the specific atomic frequency, effectively suppressing the inherent drift of the quartz crystal and imprinting the stability of the atom onto the output signal. To transform this stabilised frequency into a usable temporal epoch, a totalising counter records every cycle of the oscillator relative to a predefined starting point [5].

2.3. Performance Metrics and the Accuracy Budget

The performance of an AFR is quantified primarily through the Allan deviation (ADEV), a time-domain measure of fractional frequency instability as a function of averaging time τ. Formally, let $y(t) = [f(t) - f_0]/f_0$ denote the instantaneous fractional frequency deviation of the AFR from its nominal frequency f_0. The Allan variance, $\sigma_y^2(\tau)$, and its square root, the Allan deviation $\sigma_y(\tau)$, characterize the instability of y(t) as a function of averaging time τ by differencing the average fractional frequency in adjacent intervals of duration τ:

$$\sigma_y^2(\tau) = \frac{1}{2\tau^2} \left\langle \left\{ \int_{t_i+\tau}^{t_i+2\tau} y(t)\, dt - \int_{t_i}^{t_i+\tau} y(t)\, dt \right\}^2 \right\rangle$$

Unlike the ordinary variance, this differencing suppresses slow deterministic drift and isolates the contribution of distinct noise processes. At short averaging times ($\tau \lesssim$ 1–10 s) AFR stability is generally set by the local oscillator, after which white frequency noise from the atomic reference causes $\sigma_y(\tau)$ to improve as $1/\sqrt{\tau}$; at longer τ the AFR reaches a "flicker floor" where stability no longer improves with further averaging [5]. For GNSS AFRs, this short-term behaviour is rarely the operational bottleneck—environmental sensitivities (temperature, magnetic field, radiation) typically dominate timing error over the longer averaging times relevant to navigation [5], as discussed below. For a space-grade Rubidium Atomic Frequency Standard (RAFS), typical ADEV values are in the range of 1–2 $\times$ 10^{-12} at τ = 1 s, decreasing to approximately 10^{-14} at τ = 86,400 s (one day) [3–5].

A Passive Hydrogen Maser (PHM) achieves approximately 10^{-13} at 1 s; comparative analyses of in-orbit GNSS clocks confirm that Galileo PHMs and the latest-generation GPS Block IIF/III RAFS deliver better short-term ADEV than the other GNSS clocks examined [5,16]. In addition to frequency instability, space-qualified AFRs must satisfy stringent budgets for frequency drift (ageing), environmental sensitivity coefficients (temperature, magnetic field), radiation tolerance, and mechanical shock and vibration resistance—requirements far more demanding than those for ground-based laboratory standards.

An operationally critical aspect of GNSS clock design is the requirement to pre-compensate for relativistic frequency shifts. A satellite clock in MEO experiences two competing relativistic effects: special relativistic time dilation caused by the satellite's orbital velocity causes the clock to run slowly relative to a ground clock; while the gravitational blueshift predicted by general relativity also affects the clock. The net effect is a gravitational-kinematic fractional frequency shift of approximately 4.464×10^{-10} relative to a ground clock [5,7,17]. To compensate, GPS satellite Rb oscillators are manufactured with a pre-adjusted nominal frequency of 10.22999999543 MHz rather than the exact 10.23 MHz ground standard [17]. A residual periodic term arising from the satellite's orbital eccentricity is applied by the user receiver via the relativistic clock correction term in the broadcast navigation message [5,17].

Beyond stochastic noise, AFR accuracy and long-term stability are limited by deterministic systematic shifts that displace the observed frequency from the unperturbed atomic transition; their characterisation is the basis of the accuracy-evaluation framework used to compare clocks across architectures and generations [1,8]. The dominant contributions to the GNSS-AFR error budget are the AC-Stark light shift (of order 10^{-12} in lamp-pumped Rb and the limiting systematic in CPT-based CSACs) [5,18]; cavity pulling ($\sim 10^{-12}$/MHz for PHMs, requiring millikelvin cavity thermal stability); the wall shift in hydrogen masers, a primary long-term PHM drift mechanism arising from collisions between H atoms and the PTFE-coated storage bulb [5,19]; the second-order Doppler shift in caesium beams (suppressed below 10^{-16} in laser-cooled fountains) [1,8]; the quadratic Zeeman shift $\Delta f = \beta B^2$, isolated by a controlled C-field and multi-layer shielding (factor $\geq 10^4$) to hold the residual below 10^{-14} [1,5]; and the black-body radiation shift, scaling as T^4 [8]. Two environmental drivers complete the picture: launch loads and on-orbit micro-vibration couple in via the g-sensitivity of the quartz local oscillator (of order 10^{-9}/g [20]), mitigated by launch-representative environment qualification (the Galileo PHM passed its full vibration profile qualification [21]), isolation mounts, and ground-segment Kalman-filter monitoring; and the MEO/LEO ionising-radiation environment progressively degrades the buffer gas cell physiochemistry in rubidium AFRs, mitigated through radiation-hardened component design and continuous monitoring against the ground-segment ensemble [3,5].

3. System Engineering of Spaceborne Atomic Clocks

The four microwave atomic frequency reference architectures surveyed in the following subsections represent the complete taxonomy of clock technologies deployed—or under active development for deployment—in the space segment of operational Positioning, Navigation, and Timing systems. The quantum operating principles common to all four architectures were established in the preceding chapter; the present chapter focuses on the system engineering of the space-qualified hardware in each case: the rubidium vapour-cell AFR, the caesium thermal beam clock, the active and passive hydrogen maser, and the chip-scale atomic clock (CSAC). For each technology the discussion covers the physics-package architecture, the space-qualification envelope, and the in-orbit performance record that underpins its role in the GNSS space segment [3–5]. The performance of these microwave atomic frequency reference architectures is compared in Table 1.

3.1. Rubidium Vapour-Cell Atomic Frequency References

Rubidium (Rb) AFRs are the primary workhorses for the GNSS space segment, deployed on GPS, BeiDou, GLONASS-K, Galileo, QZSS, and NavIC [3,5]. They offer the optimal balance between compactness, long operational lifetime (exceeding 15 years in MEO), low power consumption, and sufficient long-term frequency stability for GNSS navigation requirements. Rb clocks were pioneered for space use through collaborative efforts by Rockwell International and Efratom, leading to the units for GPS Blocks I, II, and IIA [4]. Today, hundreds of functional Rb clocks are in orbit across major GNSS systems [3,5]. The present subsection focuses on the system engineering of the two rubidium AFR families deployed in space (discharge-lamp-pumped and laser-pumped), and on their space-qualification envelopes.

Discharge-lamp-pumped rubidium frequency references constitute the majority of atomic clocks used in the GNSS space segment [3]. A discharge-lamp-pumped Rb AFR is a passive device where a crystal oscillator serves as the frequency source and a passive atomic discriminator generates a correction signal that locks the oscillator to a stable atomic reference.

In order to create an AFR, four key functions must be implemented: (1) confinement of an atom population, (2) preparation and state selection, (3) interrogation, and (4) detection. In the discharge-lamp-pumped Rb AFR, confinement is implemented using sealed buffer-gas cells, state selection is achieved via optical pumping, interrogation is performed via a microwave field, and detection is performed by a photodetector [1].

The working principle exploits the energy quantum states of the isotopes ^{87}Rb and ^{85}Rb. The ^{87}Rb clock transition occurs at approximately 6.835 GHz between F = 1 and F = 2 of its $5S_{1/2}$ ground state. By exciting a ^{87}Rb vapour lamp with a radiofrequency discharge, it emits photons corresponding primarily to 5P–5S transitions. Due to the overlapping absorption spectra of ^{87}Rb and ^{85}Rb, the (5P $\rightarrow$ 5S, F = 2) transition photons are absorbed by a ^{85}Rb isotopic filter cell. The (5P $\rightarrow$ 5S, F = 1) photons pass through the filter and enter a ^{87}Rb clock cell housed within a microwave cavity and a C-field coil. The Rb lamp, filter cell, and microwave cavity are each housed in temperature-controlled ovens. Repeated optical pumping cycles preferentially populate the F = 2 sublevel, increasing the transparency of the clock cell and strengthening the photodetector signal [1,5].

A silicon photodetector monitors light throughput to produce a discriminator signal, while magnetic shields protect the package from external interference. Light transmission reaches its minimum when the microwave cavity's RF excitation aligns with the Rb atomic resonance at approximately 6.835 GHz. The photodetector signal is used as an error signal processed by the servo amplifier to control the frequency of the crystal oscillator, implementing a frequency-lock loop. The Rb resonance is interrogated by applying a low-frequency FM dither to the microwave excitation and monitoring the resulting signal [1].

A newer generation of space Rb AFRs replaces the discharge lamp with a tunable diode laser for optical pumping. The narrow linewidth and high intensity of the laser allow far more efficient state preparation than the broadband lamp, reducing the noise floor and improving short-term frequency stability compared to lamp-pumped variants. The operational Galileo RAFS uses discharge-lamp optical pumping and achieves a frequency stability of $<4 \times 10^{-14}$ at $\tau = 10^4$ s in flight test [22]; a laser-pumped variant (the R-RAFS) is in development for next-generation Galileo, with prototype 24-h stability approaching 1×10^{-14} [4]. Laser-pumped units are expected to exhibit slower long-term degradation, supporting the 12-year payload lifetime requirement of Galileo satellites [22].

Space-qualified RAFS must satisfy demanding performance envelopes: ADEV below 5×10^{-14} at one day, frequency ageing rate below 5×10^{-14} day^{-1}, temperature coefficient below 1×10^{-12} °C^{-1}, magnetic-field sensitivity minimised by multi-layer shielding, and

radiation tolerance qualified for the MEO total-ionising-dose environment [3–5]. Long-term changes in the lamp and vapour-cell physiochemistry (cell walls and buffer-gas composition) are the primary degradation mechanisms in space Rb AFRs, managed through radiation-hardened component design that supports operational lifetimes exceeding 15 years in MEO orbit [3,5].

3.2. Caesium Thermal Beam Atomic Frequency References

Caesium (Cs) thermal beam AFRs established the standard for high-accuracy frequency metrology during the second half of the 20th century and remained the dominant technology until the advent of laser-cooled Cs fountain clocks in the 1990s [8]. The international community in 1967 redefined the SI second as exactly 9,192,631,770 periods of the Cs hyperfine transition between the F = 3, m_F = 0 and F = 4, m_F = 0 ground states of ^{133}Cs [1]. Cs beam clocks provide superior frequency accuracy because the atoms are relatively free from external perturbations: they do not suffer from buffer gas collisions (as in Rb clocks) or wall interactions (as in H-masers). A crucial distinction must be drawn between frequency accuracy—the ability to realise the SI second without systematic bias—and frequency stability, the ability to reproduce the same frequency interval after interval. Cs beam clocks excel in accuracy but are constrained by finite lifetime due to Cs supply depletion, larger size, and higher power compared to Rb standards [1].

The operation begins in a high-vacuum chamber where Cs metal is heated in an oven containing narrow channels to create a collimated effusive beam. Caesium's low melting point (approximately 28 °C) and favourable vapour pressure make it well suited for this purpose [1]. This beam passes through a magnetic field gradient (the "A magnet"), which utilises the Stern–Gerlach effect to filter for atoms in the F = 3 state to pass into the interaction region [1].

Once filtered, the atoms enter an X-band waveguide known as the Ramsey cavity. The Ramsey method of separated oscillatory fields allows atoms to interact with a microwave field tuned to 9.2 GHz at two distinct locations separated by a field-free drift region. This dual interaction creates a quantum interference pattern called a Ramsey fringe. The spectral linewidth of this fringe is approximately $\Delta f \approx v/2L = 1/2\Delta t$, with v the atom velocity, L the drift region length, and Δt the transit time between the two interaction zones. Increasing the drift region length improves frequency resolution and accuracy but reduces atom flux and increases mass and volume [1].

After the second microwave interaction, the "B magnet" deflects atoms based on their final quantum state. Atoms that transitioned to the F = 4 state are detected by a hot-wire ioniser and an electron multiplier. This ionisation current allows the feedback control system to lock the LO to the peak of the atomic transition. A uniform C-field is applied across both interaction regions to resolve the Zeeman sublevels and isolate the m_F = 0 clock transition. Multiple layers of magnetic shielding minimise external field perturbations [1].

In the context of GNSS, Cs beam clocks were deployed on GPS Block IIF satellites (one per satellite, each supplied alongside two redundant Rb AFRs) and used in the GLONASS-M constellation [4,5,7,23]. Their operational use in space has been eclipsed by Rb standards due to finite consumable lifetime, larger mass, and greater complexity. However, at national metrology institutes—including NIST (USA), PTB (Germany), SYRTE (France), and NPL (UK)—primary Cs fountain clocks such as PTB-CSF2 realise the SI second with fractional frequency uncertainties below 2×10^{-16} [8,24]. In these cold-atom fountain clocks, Cs atoms are laser-cooled to microkelvin temperatures and launched through a microwave cavity, achieving Ramsey linewidths of approximately 1 Hz that greatly suppress the second-order Doppler shift relative to thermal beam clocks [5,8]. Their output feeds directly

into the international atomic time scale TAI via the Bureau International des Poids et Mesures (BIPM), providing the metrological foundation for all GNSS time scales [4,8].

3.3. Active and Passive Hydrogen Masers

An H-maser AFR is based on the transition between the F = 0 and F = 1 hyperfine levels in the ground state of atomic hydrogen at 1.420405751 GHz. Molecular hydrogen stored in a gas tank is dissociated into individual H atoms through an electronic discharge. The H atoms pass through a magnetic field gradient that acts as a state selector and guides atoms in the F = 1, m_F = 0 sublevel into a storage bulb. The interior of the bulb is coated with polytetrafluoroethylene (PTFE), allowing H atoms to bounce off the walls with negligible probability of undergoing a state transition [4]. Around the storage bulb is a cylindrical microwave cavity adjusted to resonate at precisely 1.420405751 GHz, matching the energy gap between the F = 0 and F = 1 clock states [5,19,22,25].

By accumulating sufficient hydrogen atoms in the F = 1 level, the decay from F = 1 to F = 0 can exceed a threshold via stimulated emission, causing the system to become a self-oscillating microwave generator: the active H-maser. In the passive H-maser (PHM) configuration, the system is operated below the oscillation threshold; the hydrogen clock transition is excited by an external microwave source and the device functions as a high-Q discriminator. A passive maser is more cost-effective and simpler to build than its active counterpart: while the signal-to-noise ratio is lower, the passive configuration provides excellent frequency stability adequate for the mass, volume, and power constraints of a satellite platform [4,5,22].

PHMs in the GNSS space segment—aboard Galileo satellites and on selected BDS-3 experimental satellites [26,27]—are passive masers. The Galileo PHM represents the state of the art for spaceborne microwave clocks; its architecture, developed by Galileo Avionica with the Observatory of Neuchâtel and Temex Neuchâtel Time, employs a magnetron-type microwave cavity with two-stage active thermal control and a triple magnetic shield, exploits the in-orbit space vacuum for thermal isolation of the cavity, and uses a patented single-modulation dual-servo loop to lock the ultra-stable crystal oscillator to the hydrogen resonance while simultaneously tuning the cavity via an Automatic Cavity Tuning (ACT) system [21]. The cavity-pulling systematic requires the microwave cavity to be temperature-stabilised to within millikelvins, and the wall shift is a primary source of long-term frequency drift in spaceborne PHMs [5,21,25].

A comparative summary of the three primary spaceborne AFR technologies illustrates the trade space: Rb AFRs provide the best compromise between compactness and long-term stability and are the most widely deployed; PHMs offer the best stability at a significantly larger physical footprint; Cs beam clocks deliver high absolute accuracy but are limited in space applications by lifetime and mass. Active H-masers in the ground segment provide the highest stability of all deployed atomic clock technologies and underpin the system-level timekeeping that enables GNSS to achieve its navigation performance [3–5]. The complementary characteristics of RAFS and PHM are exploited in next-generation Galileo satellite designs, where an on-board clock ensemble (the One Clock Ensemble, or ONCLE) combines the satellite's multiple RAFS and PHM units into a single disciplined timescale to enhance both frequency stability and fault tolerance [28].

3.4. Chip-Scale Atomic Clocks

The development of CSACs represents a decades-long effort to miniaturise high-precision timekeeping for portable and space applications, largely driven by DARPA's interest in secure communications and satellite-based navigation [11,12]. The commercial launch of the Microsemi SA.45s CSAC in 2011 marked the transition from research pro-

totype to available hardware; today's production units occupy less than 17 cm^3, weigh approximately 35 g, consume less than 120 mW of power, and operate across −40 to 85 °C [11,12]. This miniaturisation was enabled by two key breakthroughs: low-power Vertical Cavity Surface Emitting Lasers (VCSELs), which allow optical pumping using less than 5 mW, and Micro-Electro-Mechanical Systems (MEMS) fabrication, which enables millimetre-sized atomic vapour cells in compact packages [11].

CPT differs fundamentally from the direct microwave excitation used in the AFRs above. Two ground-state hyperfine sublevels couple to a common excited state via two optical fields; when their two-photon (Raman) detuning matches the hyperfine splitting, the atoms collapse into a non-absorbing "dark state" superposition. The resulting transmission peak locks the local oscillator. Since the coherence is created optically rather than by a microwave cavity, CPT removes the cavity-size constraint ($\geq\lambda/2$, or 2.2 cm for ^{87}Rb) that otherwise limits miniaturisation [11]. A VCSEL modulated at half the 9.193 GHz hyperfine frequency generates sidebands that, when simultaneously resonant with both ground-state sublevels, establish CPT. The clock locks the modulation frequency to the resulting transmission peak, imprinting the stability of the 9.193 GHz Cs transition on the output [11]. The light shift is the dominant systematic for CPT-based clocks, and pulsed interrogation schemes are being developed to suppress it in next-generation units.

The short-term frequency stability of CSACs is on the order of 10^{-10} at 1 s and their long-term stability is limited by frequency drift of approximately 10^{-11} per month, significantly inferior to space-grade RAFS or PHM but adequate for holdover timing in GNSS-denied environments. CSACs are increasingly considered for small satellites, UAVs, and distributed sensor networks where size, weight, and power are primary constraints [11].

An important application for CSACs is LEO-PNT, where the clock maintains stable frequency output between GNSS synchronisation events, enabling continuous PNT signal broadcast [2]. Tzanoulinos et al. demonstrated that Walker Delta CubeSat constellations equipped with CSACs can deliver persistent PNT coverage over a country-sized area, making the CSACs and CubeSats key enabling technologies for the emerging LEO-PNT ecosystem [12,13].

Despite the extraordinary miniaturisation achieved, commercial CSACs remain significantly less stable than space-grade RAFS units in long-term frequency stability [11]. Research focuses on reducing the light shift through pulsed CPT interrogation, improving cell fabrication uniformity, and developing buffer-gas mixtures with reduced temperature sensitivity, with the goal of improving long-term stability [11]. Moreover, CSACs are increasingly integrated into terrestrial and airborne platforms to provide precision timing holdover in GNSS-denied or GNSS-contested environments [11]. This cross-platform footprint highlights the CSAC's role as a core technology wherever size, weight, and power constraints dominate.

Table 1. Cross-technology performance comparison of the four microwave AFR architectures.

Metric	Cs Thermal Beam	RAFS (Rb Lamp-Pumped)	PHM (Passive H-Maser)	CSAC (CPT-Based)
Short-term ADEV σ_y (1 s)	~1.6×10^{-11} [4]	~1–2×10^{-12} [4]	~6×10^{-13} [4]	~10^{-10} [11]
Long-term ADEV σ_y (1 day)	~5.4×10^{-14} [4]	~3×10^{-15} [4]	~7×10^{-15} [4]	~10^{-11} [11]
Operational lifetime	Limited by Cs consumable; shorter than RAFS [4]	≥12 years (Galileo req.) [3,22]; 10–15 years GNSS design life [4]	12 years (Galileo req.); limited by H_2 supply and ion pump [22]	>6 years at 85 °C (accelerated testing) [11]

Table 1. *Cont.*

Metric	Cs Thermal Beam	RAFS (Rb Lamp-Pumped)	PHM (Passive H-Maser)	CSAC (CPT-Based)
SWaP (mass/volume/power)	~13 kg/~14 L/~30 W [4]	~3.3–7 kg/~2.4–5 L/~30 W [4,22]	~18–25 kg/~28–40 L/~55 W [4,22]	~0.035 kg/~0.02 L/~0.12 W [12]
Radiation tolerance	High inherently; no discharge lamp or buffer-gas cell [3,4]	Qualified for MEO TID; lamp and buffer-gas cell are principal degradation paths [3,18]	Qualified for MEO TID; H_2 supply and ion pump degrade under ionising radiation [22]	Physics package: 43 krad (Si) TID (~1 yr LEO); TCXO failed below that threshold [11]

3.5. Optical Atomic Frequency Standards

Optical atomic clocks lock a probe laser to an electronic transition in the visible or ultraviolet range, at frequencies of 10^{14}–10^{15} Hz—five orders of magnitude above the microwave hyperfine transitions exploited by the AFRs surveyed in Sections 3.1–3.4. Because the quality factor $Q = \nu/\Delta\nu$ scales with carrier frequency, this shift yields a fractional frequency stability and accuracy approximately two orders of magnitude better than the best microwave standards [8]. State-of-the-art ground-based optical clocks have demonstrated fractional uncertainties at or below 1×10^{-18} [8,29], compared with the ~1.7×10^{-14} at 900 s averaging achieved by the Galileo FOC clock ensemble—the most stable satellite clock configuration currently in orbit [29].

Two architectures dominate the field. The absence of wall collisions in single trapped-ion clocks eliminates the drift mechanism that limits microwave cell standards [30]. Optical lattice clocks trap large ensembles of neutral atoms—most commonly ^{87}Sr or ^{171}Yb—at a species-specific "magic wavelength" at which the AC Stark shift from the trapping light cancels on both clock levels, and achieve stabilities approaching 10^{-18} with signal-to-noise benefits from the large atom number [8,29]. Both architectures rely on the optical frequency comb to bridge the gap between the optical clock frequency and the microwave domain for signal distribution [29].

The principal barrier to space deployment is SWaP: a transportable Sr lattice clock currently occupies ~968 L and 250 kg, against the 40-L, 25-kg envelope of the Galileo PHM [29]. The ESA Space Optical Clock (SOC/SOC2) project addressed this directly, developing compact modular Sr and Yb demonstrators with low-power laser systems and permanent-magnet atom sources. The SOC2 demonstrator targets an instability below $1 \times 10^{-15}\ \tau^{-1/2}$ and an inaccuracy of 5×10^{-17}, while the full space mission goal is a more demanding inaccuracy below 1×10^{-17}, within an ISS-compatible form factor [31]. The current institutional roadmap proceeds from ACES—whose cold-atom microwave PHARAO clock (Section 6.2) validates space-to-ground link infrastructure and microgravity clock operation [32]—through the OACESS ISS pathfinder concept, which would operate an optical clock aboard an Earth-orbiting space station and conduct searches for physics beyond the Standard Model [33], to the FOCOS mission, which would place a Yb lattice clock on a highly eccentric orbit to test the gravitational redshift with sensitivity 30,000 times beyond current limits [34].

From a PNT standpoint, optical clocks could reduce clock-induced range errors to below 1 mm within 30 s of observation, and deliver at least tenfold better timing performance than the Galileo FOC clock ensemble at 900 s of averaging [29]. For dedicated LEO-PNT constellations, this stability advantage directly extends the autonomous orbit determination and time synchronisation interval between ground contacts—a critical driver for the Dedicated LEO-PNT architecture class discussed in Section 5. Closing the

remaining SWaP and TRL gaps is the primary objective of the SOC–OACESS–FOCOS mission sequence [29,31,33,34].

4. Atomic Clocks in GNSS Constellations

A minimum of four simultaneously visible satellites are required to determine a user's three-dimensional position and clock offset via trilateration of pseudoranges. The onboard AFR generates the frequency reference from which the ranging signal is synthesised and broadcasted; the ground control segment periodically uplinks a clock correction polynomial—typically a second-order fit in time—to compensate for residual AFR drift and maintain each satellite's broadcast time aligned to the system timescale within the service-level budget [7]. The quality of the onboard AFR therefore directly constrains both the ranging accuracy and the required cadence of ground correction uplinks. Each of the four primary GNSS constellations employs a distinct combination of atomic clock technologies, reflecting different design philosophies, national industrial capabilities, and programmatic timelines [3,4].

Table 2 summarises the space-segment parameters of the four global constellations; Table 3 summarises their primary clock technologies and one-day stability.

Table 2. Space-segment parameters of the four global GNSS constellations. In-orbit spare counts are approximate and subject to operational status changes [3,4].

Parameter	GPS (USA)	Galileo (EU)	GLONASS (Russia)	BeiDou-3 (China)
Nominal satellites	24 (31+ active)	24	24	35 (3 GEO, 3 IGSO, 24 MEO and 5 exp.) [35]
Inclination	55°	56°	64.8°	55° (MEO/IGSO); 0° (GEO)
Orbital pattern	Walker 24/6/1	Walker 24/3/1	Walker 24/3/1	Hybrid (GEO, IGSO and Walker MEO)
In-orbit spares	∼7	6 (2 per plane) [36]	3 [37]	2 MEO (launched September 2024) [38]
Altitude (km)	20,200	23,222	19,100	MEO: 21,528; GEO: 35,786

Table 3. Primary atomic clock technologies deployed across major PNT constellations by satellite block and one-day Allan deviation performance tier.

Constellation	Block/Generation	Primary Clock Type	One-Day ADEV
GPS (USA)	Block IIF	RAFS (Rb)	$\sim 3 \times 10^{-15}$ [4]
GPS (USA)	Block III	RAFS (Rb), advanced	$\sim 3 \times 10^{-15}$
Galileo (EU)	G1	PHM (primary)/RAFS (backup)	$\leq 3 \times 10^{-15}/\sim 4 \times 10^{-14}$
GLONASS (Russia)	GLONASS-M	Cs thermal beam	$\sim 1 \times 10^{-13}$
GLONASS (Russia)	GLONASS-K1	RAFS (Rb)	$\sim 5 \times 10^{-14}$
BeiDou (China)	BDS-3 MEO	RAFS (Rb)	$\sim 8.6 \times 10^{-15}$ [27]
BeiDou (China)	BDS-3 MEO	PHM	$\sim 1 \times 10^{-15}$ [39]
QZSS (Japan)	QZSS-1/2/3/4	RAFS (Rb)	$\sim 5 \times 10^{-14}$ [40]

4.1. GPS

The GPS, operated by the United States Space Force, maintains a nominal constellation of 24 satellites distributed across six orbital planes at an altitude of 20,200 km and an inclination of 55°. The planes are separated by 60° in right ascension of ascending node (RAAN), with approximately four satellite slots per plane in a non-ideal Walker-delta arrangement [7]. The control segment can support up to 31 operational satellites, with the surplus beyond the nominal 24 providing redundancy and in-orbit spares [7]. The design orbital period is approximately 11 h 58 min (half a sidereal day), ensuring that the ground

track repeats daily and that at least four satellites are visible from anywhere on Earth at all times [7].

The atomic clock heritage spans five generations. Block I through IIA satellites used Cs beam and Rb gas cell clocks [4]. Block IIF (2010–2016) introduced a mixed configuration of two Rb and one Cs clock per satellite [23], with Rb one-day ADEV around 3×10^{-15} for life-tested units [4]. GPS Block III (first launch December 2018) carries three RAFS per satellite [3,16], supplied by Excelitas Technologies [5], achieving one-day ADEV in the low 10^{-15} range as confirmed by in-orbit analysis of the first Block III satellite ("Vespucci") [41]. The Block III RAFS exhibits improved short-term stability compared to Block IIF for integration times up to 10 s [41]. Block III satellites have a 15-year designed operational lifetime and introduce the L1C, L2C, and L5 civil signals [41].

4.2. Galileo

Galileo is the GNSS of the European Union, managed by the European Union Agency for the Space Programme (EUSPA) in cooperation with ESA. The full operational constellation comprises 24 MEO satellites distributed across three orbital planes (Walker 24/3/1 configuration) at an altitude of 23,222 km and an inclination of 56°. Each plane contains eight evenly spaced satellite slots separated by 45° in argument of latitude. The orbital period is approximately 14 h 5 min [36]. Galileo declared Initial Services on 15 December 2016 [42], with Full Operational Capability achieved progressively as subsequent satellite launches completed the Walker 24/3/1 configuration.

Each Galileo satellite carries four atomic clocks in a dual-technology, quadruple-redundant configuration: two RAFS and two PHMs [5,22]. The operational Galileo RAFS, manufactured by Temex Neuchâtel Time with discharge-lamp optical pumping, achieves fractional frequency stability of $<4 \times 10^{-14}$ at $\tau = 10^4$ s in flight test [22]. The PHM, the most stable clock in any operational GNSS, follows the Allan-deviation specification $\sigma_y(\tau) \leq 1 \times 10^{-12}\ \tau^{-1/2}$ over 1 s $\leq \tau \leq 10^4$ s—roughly one order of magnitude better than the best Rb standards in the constellation [5,21]. A comparative analysis confirms that Galileo PHMs and the latest-generation GPS Block IIF/III RAFS demonstrate better short-term ADEV than the other GNSS clocks examined [16]. The quadruple-redundant clock architecture kept all satellites operational during the 2017 clock anomalies, in which several rubidium and passive-hydrogen-maser units ceased operating; ESA reported that the rubidium-clock failures shared a consistent signature linked to probable short circuits, possibly associated with a particular ground test procedure [43].

The Galileo PHM was first flown aboard the GIOVE-B experimental satellite, the first to carry an orbiting passive hydrogen maser [3]. Its engineering model was developed and validated at the Observatory of Neuchâtel [21,25]. For the Second Galileo Generation programme (G2G), ESA awarded contracts in 2021 for an evolved clock configuration: Leonardo supplies two PHMs per satellite, while Orolia (Safran Group) supplies three RAFS, increasing the onboard clock complement from four to five units per satellite and enabling the One Clock Ensemble (ONCLE) architecture for enhanced fault tolerance [28,44,45].

4.3. GLONASS

GLONASS is the Russian Federation's GNSS, operated by the Russian Aerospace Defence Forces. The full constellation consists of 24 satellites distributed across three orbital planes at an inclination of 64.8° and an altitude of 19,100 km. Each plane contains eight evenly spaced slots, with the three planes separated by 120° in RAAN. The orbital period is approximately 11 h 15 min, and the high inclination of 64.8°—the highest among the four global systems—provides improved coverage at high latitudes and is the primary design driver distinguishing GLONASS from GPS [7]. Legacy GLONASS satellites employ

Frequency Division Multiple Access (FDMA), with each satellite transmitting on a slightly different carrier frequency, in contrast to the Code Division Multiple Access (CDMA) approach used by GPS, Galileo, and BeiDou [7].

GLONASS-M satellites carry onboard Cs atomic beam frequency standards, with short-term clock-offset prediction accuracy of approximately 0.52 ns and fitting precision (residual standard deviation) of approximately 0.88 ns—both inferior to the equivalent figures for the rubidium equipped GPS Block IIF, BDS-2, QZSS, and Galileo PHM constellations [46]. The Cs clocks exhibit a frequency instability of approximately 4×10^{-13} at 1000 s and approximately 1×10^{-13} at 10,000 s [23,46]. These values place GLONASS at the lowest tier of clock performance among the four global constellations. The GLONASS-K1 satellites, launched in 2011 and 2014, each carry two Cs beam clocks and two Rb AFRs [3] and transmit the first GLONASS CDMA signal; the GLONASS-K2 generation is designed to add further CDMA signals [7]. Clock corrections are uplinked by the ground control segment to maintain GLONASS System Time (GLONASST) within required bounds [7].

4.4. BeiDou

BDS-3, declared globally operational in July 2020, constitutes a hybrid global constellation combining three distinct orbit types: 3 Geostationary Earth Orbit (GEO) satellites at 35,786 km altitude and 0° inclination, providing stationary coverage over the Asia-Pacific region; 3 Inclined Geosynchronous Satellite Orbit (IGSO) satellites at approximately 35,786 km altitude and 55° inclination, tracing a figure-of-eight ground track; and 24 MEO satellites at approximately 21,528 km altitude and 55° inclination, distributed across three orbital planes [3,5,35]. An additional five experimental BDS-3 satellites—two in IGSO and three in MEO—were launched between 2015 and 2016 for technology validation purposes [26].

BDS-2 satellites carry Rb AFRs manufactured by China Aerospace Science and Technology Corporation (CASC), with frequency stability in the 2.0–4.5 $\times 10^{-14}$ range at ~30,600 s averaging based on long-term clock-product analysis [47]. BDS-3 operational satellites carry redundant improved Rb AFRs (CASC) or, on a subset of MEO satellites, PHMs (CASC/SECM); among the five experimental satellites, two—one IGSO and one MEO—carried PHMs of indigenous Chinese design [26,27,47]. The BDS-3 Rb clocks represent a marked improvement over BDS2 [27], and the BDS-3 PHM delivers stability comparable to the Galileo PHM [26]. According to the official BeiDou specification, BDS-3 satellites carry rubidium clocks with a stability of order 10^{-14} and passive hydrogen masers with a stability of order 10^{-15} [39]. The BDS-3 PHM clock-offset standard deviation across operational arcs has a typical value of approximately 0.21 ns [27]. The performance improvements represent a major national investment in space-qualified frequency standards and have established China as a leading contributor to GNSS-grade clock technology globally [3,4].

4.5. Space-Based Augmentation and Regional Navigation Satellite Systems

Two further classes of system supplement the four global constellations: Space-Based Augmentation Systems (SBAS), which broadcast differential corrections and integrity information from geostationary platforms, and regional navigation satellite systems—QZSS over Japan and NavIC over the Indian subcontinent—which provide standalone or augmented PNT service over a defined service area, each with its own orbital architecture and atomic-clock payload.

4.5.1. Space-Based Augmentation Systems

SBAS are overlaid upon core GNSS constellations to provide differential corrections, integrity monitoring, and ranging signals for safety-of-life applications, particularly civil aviation precision approach. The principal operational SBAS include WAAS (North America), EGNOS (Europe), MSAS (Japan), and GAGAN (India) [7]. SBAS geostationary satel-

lites do not carry primary atomic frequency standards. Precise timing in SBAS networks originates from the ground segment: Wide Area Reference Stations or Ranging and Integrity Monitoring Stations (RIMS) provide precise network time references [7]. The GEO satellites broadcast these corrections in real time, enabling SBAS-aided positioning to support precision approach guidance in civil aviation [7]. The quality of SBAS correction messages depends directly on the performance of the ensemble of ground-station atomic clocks at the Wide Area Reference Stations and Ranging and Integrity Monitoring Stations, referenced to GNSS time scales and UTC [7].

4.5.2. QZSS

Japan's QZSS provides regional augmentation over Japan and the Asia-Oceania region [7]. The operational constellation consists of four satellites: three in quasi-zenith orbits (highly inclined elliptical orbits) and one in geostationary orbit [3,40]. The quasi-zenith orbit ensures that at least one satellite is at high elevation over Japan at all times, providing resilient signal availability in urban canyons [7]. Michibiki-1 (QZS-1, launched 11 September 2010) carries two redundant Rb AFRs [3,40]. All four operational QZSS satellites (QZS-1 through QZS-4) carry Rb AFRs, with in-orbit one-day ($\tau = 10^4$ s) frequency stability of approximately 5.3–5.4 $\times$ 10^{-14} for the three IGSO satellites (QZS-1/J01, QZS-2/J02, QZS-4/J03) and approximately 2.6 $\times$ 10^{-14} for the GEO satellite (QZS-3/J07) [40].

4.5.3. NavIC

NavIC (initially named Indian Regional Navigation Satellite System, IRNSS), developed by ISRO, is a fully operational regional system that provides positioning and timing services over India and the surrounding region, broadcasting in the L5 (1176.45 MHz) and S (2492.028 MHz) bands [48]. The constellation comprises seven satellites—three in geostationary orbit and four in inclined geosynchronous orbit at 29° inclination (orbital radius 42,164 km, one sidereal-day period)—and the satellites use rubidium clocks for timekeeping [7]. Nine IRNSS satellites were launched between 2013 and 2018; the first, IRNSS-1A, carried three rubidium atomic frequency standards built by SpectraTime [3], and subsequently suffered an on-board atomic-clock failure that illustrates the operational criticality of the clock payload [48].

5. LEO-PNT: Atomic Clocks in Low Earth Orbit

LEO-PNT represents a fundamentally different approach to satellite navigation, in which navigation signals are broadcast from satellites at altitudes below 2000 km [2]. Free-space path losses from LEO are typically around 20 dB lower than those of MEO GNSS signals at an altitude of 600 km [10]; although this free-space advantage does not translate directly into an equivalent increase in received signal power the link-budget benefit is nonetheless substantial [10,13]. LEO satellites additionally offer a faster-changing geometry that accelerates positioning convergence and reduces time-to-first-fix [2,10]. The use of frequency bands orthogonal to legacy GNSS allocations provides further resilience against jamming and interference [9,10,14].

Menzione and Paonni proposed a taxonomy of LEO-PNT architectures with distinct atomic-clock requirements; the three classes most relevant to onboard clocks are [9]: In Signals of Opportunity (SoP), existing non-navigation LEO signals—such as those of commercial broadband constellations—are repurposed as ranging observables without modification of the host spacecraft; the operator of the PNT service does not control the space segment and all complexity resides in the user receiver, so no dedicated AFR is required on the LEO platform beyond whatever oscillator the communications satellite natively carries [9]. In Fused LEO-PNT architectures, each LEO satellite carries a GNSS

receiver and a navigation transmitter; the LEO clock is continuously disciplined to the MEO GNSS timescale via on-board Orbit Determination and Time Synchronisation (ODTS), so the onboard AFR must provide short-term stability sufficient to maintain phase coherence between successive MEO synchronisation events but need not guarantee long-term autonomous performance. A CSAC or miniaturised RAFS is adequate for this role [9]. In Dedicated LEO-PNT, by contrast, the constellation must perform autonomous ODTS onboard and broadcast ephemeris and clock corrections independently of the GNSS infrastructure, raising the onboard AFR stability requirement to GNSS-grade levels [9,10].

Ries et al. assessed LEO-PNT as a strategic augmentation for European PNT capabilities, noting that space-based PNT is the largest downstream space sector globally, worth approximately e150 billion per year [10]; the paper evaluated system concepts spanning a hosted payload on the EU's IRIS2 secure connectivity constellation (Infrastructure for Resilience, Interconnection & Security by Satellites), a dedicated concept studied under the ELCANO project, and hybrid architectures combining features of both, with the common finding that state-of-the-art Precise On-board Orbit Determination (P2OD) achieving decimetric orbit accuracy is a prerequisite for meeting signal-in-space range error budgets, since the short LEO altitude amplifies the projection of residual orbital error into user pseudorange. P2OD integrates high-fidelity spacecraft dynamics with on-board GNSS code and carrier-phase measurements—augmented by the Galileo High Accuracy Service—to deliver sub-decimetre position accuracy and sub-millimetre/s velocity estimation, enabling accurate broadcast ephemeris and clock-correction products [9,10]. The European institutional roadmap is exemplified by ESA's Celeste in-orbit demonstration under the FutureNAV programme: an 11-satellite quasi-polar constellation at 500–600 km altitude exploring LEO-PNT signal concepts in L-, S-, C-band, and UHF, whose first two Pathfinder A CubeSats (a 12U from GMV, Spain, and a 16U from Thales Alenia Space, France) launched on 28 March 2026 on a Rocket Lab Electron from New Zealand, with the first navigation signal received at ESTEC on 8 April 2026 and meeting the ITU frequency-filing deadline of May 2026 [14]. From 2027 onward, additional launches are planned to bring Celeste to its full 11-spacecraft configuration, offering a wider range of experimentation opportunities across additional frequency bands [14].

Furthermore, a feasibility study by University of Athens with the support of ESA utilised orbital simulations to demonstrate that a Walker-Delta constellation comprising 100 CSAC-equipped 8U CubeSats at a 550 km altitude can provide persistent S-band PNT coverage over a country-sized region in Europe [12]. Given their short-term stability and low SWaP profile, CSACs are ideal for the CubeSat platforms defining the emerging Fused LEO-PNT class [11,12].

The commercial LEO-PNT sector has seen rapid growth alongside governmental programs. Xona Space Systems (California, est. 2019) is developing the Pulsar constellation of approximately 300 low-SWaP LEO CubeSats, targeting cm-level positioning accuracy in L- and C-band. Pulsar's patented distributed clock architecture places atomic clocks only at selected network nodes rather than aboard every satellite, and maintains synchronisation via inter-satellite links, enabling GNSS-independent operation while minimising per-platform clock complexity [9,12]. A first on-orbit demonstration payload, Huginn, was hosted on the Sherpa-AC 1 vehicle at 525 km/97° in 2022, successfully broadcasting PNT signals in both bands and validating the distributed timing scheme [12]. TrustPoint (Virginia, est. 2020) pursues a fully GNSS-independent approach by transmitting C-band (~5 GHz) ranging signals from CubeSats equipped with on-board clocks and a dedicated orbit determination and time synchronisation (ODTS) system; two technology demonstrator satellites were launched in 2023, with the constellation designed to serve an unlimited number of users without dependency on MEO GNSS infrastructure [12]. Both programmes

exemplify the Dedicated LEO-PNT architecture class, following the taxonomy of Menzione and Paonni [9].

China's commercial and government-backed programmes constitute the most extensive LEO-PNT deployment effort outside Europe. Beijing Future Navigation Technology's CentiSpace constellation—190 satellites planned across three Walker sub-constellations (Walker 120/12/1 at 975 km/55°; Walker 30/3/1 at 1100 km/87.4°; Walker 40/4/1 at 1100 km/30°)—broadcasts L1 and L5 augmentation signals to enhance BeiDou performance and enable PPP applications across all latitudes; five CentiSpace-1 pathfinder satellites were operational by October 2022, demonstrating the augmentation technique and laser inter-satellite links [12]. Zhejiang Geely's GeeSpace operates the Geely Future Mobility Constellation, targeting a complementary commercial niche: 72 satellites in Phase 1 expanding to 240, providing cm-level PPP-RTK services primarily for autonomous driving and smart mobility. The second orbital plane was completed with 11 GeeSAT-2 satellites in February 2024 [12]. Unlike the US commercial entrants, the Chinese programmes are architecturally coupled to BeiDou augmentation and align with the GNSS Augmentation dependency tier described by Menzione and Paonni, in which MEO GNSS continuously provides the orbit and timing reference, relaxing the onboard AFR requirement relative to a fully autonomous Dedicated system [9,12].

An overview of the LEO-PNT programmes mentioned above can be seen in Table 4.

Table 4. Overview of selected LEO-PNT programmes and their architecture classification.

Operator (Country)	Planned Constellation	Signal Band	GNSS Dependency	Status
Xona Space Systems (US) [12]	~300 CubeSats	L, C	Independent (ISL sync)	Huginn demo, 2022
TrustPoint (US) [12]	Microsatellites	C (~5 GHz)	Independent	2 demo sats, 2023
Beijing Future Nav. Tech. (CN) [12]	190 (3 sub-constellations)	L1, L5	BeiDou augmentation	5 operational pathfinders, by October 2022
GeeSpace (CN) [12]	240 (72 in Phase 1)	Not disclosed	BeiDou augmentation	GeeSAT-2 (11 sats), February 2024
ESA/FutureNAV (EU) [10,14]	11	L, S, C, UHF	Multi-layer (alongside Galileo)	2 Pathfinder-A sats, March 2026

6. Atomic Clocks Beyond Satellite Navigation

Beyond their central role in satellite navigation, ultra-precise atomic clocks enable a broader class of aerospace applications in which autonomous, high-stability timekeeping is either a scientific objective or an operational necessity. This chapter surveys three such application domains: deep-space autonomous navigation via NASA's Deep Space Atomic Clock (DSAC); spaceborne fundamental-physics experimentation via the ESA/CNES Atomic Clock Ensemble in Space (ACES); and precision timing in Unmanned Aerial Vehicles (UAVs), where miniaturised atomic clocks underpin holdover timing in GNSS-denied environments.

6.1. The NASA Deep Space Atomic Clock

The most significant recent development in spaceborne precision timekeeping beyond GNSS is NASA's Deep Space Atomic Clock (DSAC), developed at the Jet Propulsion Laboratory (JPL). The DSAC is a miniaturised mercury-ion linear ion-trap clock operating at a hyperfine transition frequency of approximately 40.5 GHz [30]. A demonstration unit

was launched into LEO on 25 June 2019 aboard the General Atomics Orbital Test Bed. Over its two-year mission, the DSAC demonstrated a long-term frequency stability of 3×10^{-15} after 23 days of operation, equivalent to a time deviation of less than 4 ns over that interval, and an estimated frequency drift of 3.0×10^{-16} per day [30]. These results confirm that DSAC is up to an order of magnitude more stable than the most capable operational GNSS atomic clocks over comparable timescales [30].

The DSAC navigation analogue experiment demonstrated viable one-way ranging navigation for a low-altitude Mars orbiter scenario, independent of two-way Deep Space Network contact [49].

Current deep-space missions require two-way ranging, which ties navigation solutions to ground station availability and communication delays [49]. With a clock of DSAC-class stability, a spacecraft can perform autonomous one-way ranging and independently resolve its own navigation solution, enabling a new architecture for deep-space exploration with significantly reduced ground-station dependency and greater operational autonomy [30,49].

6.2. The ESA/CNES ACES Mission

The Atomic Clock Ensemble in Space (ACES) is a joint mission of the European Space Agency (ESA) and Centre National d'Études Spatiales (CNES), operated on the Columbus External Platform Facility (EPF) of the International Space Station (ISS), where its combined clock signal is compared with ground-based atomic clocks through a dedicated microwave link. ACES was launched on 21 April 2025 aboard a SpaceX Falcon 9 (the 32nd Commercial Resupply Services mission) and installed on the Earth-facing side of the Columbus laboratory on 25 April 2025 for a planned 30-month deployment, with a six-month commissioning phase [50]. ACES represents the state of the art for space-based fundamental physics investigations with ultra-precise atomic clocks [3,51].

ACES comprises two complementary clock instruments: PHARAO, a laser-cooled caesium clock developed by CNES and Observatoire de Paris, and SHM (Space Hydrogen Maser), an active H-maser developed by Spectratime, Switzerland. PHARAO achieves frequency instability approaching 10^{-16} over one day by laser-cooling Cs atoms and launching them through a Ramsey microwave cavity, exploiting the extended atomic interaction time available in the microgravity environment to achieve a Ramsey linewidth far narrower than any ground-based Cs beam clock. The SHM provides superior short-term frequency stability, bridging the performance gap at observation timescales below 10^4 s where the PHARAO signal-to-noise ratio is limited [3,51].

The combined ACES clock signal serves two principal scientific objectives: tests of the gravitational redshift predicted by general relativity at the 2×10^{-6} level via comparative measurements with ground-based atomic clocks using a dedicated microwave link (MWL); and searches for violations of local position invariance and possible variation of fundamental constants. The PHARAO and SHM technologies together validate and demonstrate the performance of laser-cooled caesium and active H-maser architectures for future generations of spaceborne precision clocks [3,51].

6.3. Atomic Clocks in Unmanned Aerial Vehicles

The rapid proliferation of Unmanned Aerial Vehicles (UAVs) across civil, commercial, and defence applications has created a growing operational requirement for autonomous, precise timing references that do not depend continuously on GNSS signals. UAV operations are increasingly conducted in environments where GNSS is unavailable, unreliable, or actively degraded through jamming, spoofing, or multipath—for example, urban canyons, indoor transition zones, contested airspace, and dense sub-canopy environments. In such scenarios, an onboard atomic clock provides critical timing holdover capability: main-

taining a stable time reference for a defined duration after loss of GNSS synchronisation, allowing continued autonomous navigation and coordinated operation. The chip-scale atomic clock has emerged as the core technology for this role thanks to its compact size, weight, and power envelope [11].

The Chip-Scale Atomic Clock (CSAC), whose operating principle and performance envelope have been described earlier, is the enabling technology for this application domain. Its exceptional miniaturisation—less than 17 cm^3, approximately 35 g, under 120 mW—makes it uniquely compatible with the stringent size, weight, and power (SWaP) budgets of tactical and reconnaissance UAV platforms of all scales [12]. The CSAC's short-term frequency instability of order 10^{-10} at 1 s integration time enables timing holdover after GNSS loss [11].

Current CSACs remain less stable than RAFS or PHM space clocks over long averaging times ($\tau > 10^4$ s), which limits autonomous holdover duration. Emerging research directions specifically relevant to improving UAV timing performance include the following: (1) pulsed coherent population trapping (CPT) interrogation schemes to suppress the AC Stark-shift systematic and thereby improve the CSAC flicker-noise floor; (2) advances in MEMS-based vapour-cell fabrication to reduce temperature sensitivity and miniaturisation constraints; and (3) development of miniaturised Rb vapour-cell standards that bridge the performance gap between conventional CSACs and space-grade RAFS whilst remaining within compact size, weight, and power budgets [11].

7. Challenges and Future Directions

The maturity of spaceborne AFR technology demonstrated across the major GNSS constellations masks three structural bottlenecks that will govern the pace of progress in emerging platforms, from LEO-PNT constellations to fundamental-physics missions.

7.1. Space Environmental Degradation and the Path to Optical Clocks

Current spaceborne AFR technologies face well-documented degradation under operational space conditions. Sensitivity to radiation-induced degradation—including progressive shifts in oscillator base frequency over mission lifetime—remains a recognised qualification challenge for both rubidium vapor-cell and quartz-based components [3]. The AC Stark shift couples lamp thermal fluctuations into frequency output across multi-year mission lifetimes, as demonstrated by decade-long in-orbit records of GPS RAFS units [18]. Thermal cycling through eclipse and sunlit orbital phases contributes to systematic frequency drift in multi-component physics packages [5], and for PHMs, outgassing and ion pump degradation impose long-term stability limits absent in ground installations [19]. These effects are visible in the Galileo clock anomaly episode of 2017 [43], drift trends in GLONASS operational clocks [46], and BDS clock product evolution [47].

The long-term solution lies in next-generation clock architectures that trade microwave hyperfine transitions for optical-frequency ones. Optical lattice clocks (neutral Sr or Yb in a magic-wavelength trap) and trapped-ion optical clocks (Al^+ or Yb^+ in a Paul trap) have achieved systematic fractional frequency uncertainties below 10^{-18} in ground laboratories—approaching three orders of magnitude beyond the best operational GNSS clocks [8]. The NASA Deep Space Atomic Clock demonstrated that trapped-ion technology can survive launch loads and the space radiation environment, reaching between 3 and 5×10^{-15} one-day instability in orbit [30,49]. The ESA/CNES ACES mission with its PHARAO laser-cooled caesium clock further advances cold-atom technology in space [50,51]. However, both DSAC and PHARAO interrogate microwave transitions; the step to optical-frequency equivalents demands space-qualified optical frequency combs, narrow-linewidth laser sources with multi-year lifetimes, and vibration-isolated optical cavities—none yet in-

tegrated into a complete spaceborne optical frequency standard [8]. Galileo's second-generation programme, opting for active hydrogen masers over optical clocks [44], reflects a realistic near-term assessment of space-qualification readiness. Spaceborne optical clocks in a navigation role remain a 15–20 year development horizon.

7.2. SWaP–Performance Tradeoffs for Smallsat Platforms

The CSAC is currently the only AFR technology compatible with CubeSat mass, volume, and power budgets, achieving this through coherent population trapping at approximately three orders of magnitude penalty in stability relative to space-grade RAFS [11]. A CSAC at 10^{-11} one-day Allan deviation accumulates ~1 µs of free-running timing error per day against the 3 ns budget required for 1-m positioning [2,11], a gap that must be compensated through frequent ground contact or inter-satellite links, undermining the autonomous holdover capability motivating onboard clocks in the first place [9,12]. Closing this gap requires either miniaturised laser-pumped Rb standards bridging CSAC and RAFS performance [3], or constellation architectures tolerant of higher holdover errors through geometry and signal-processing design [12].

7.3. Fault-Tolerant Multi-Clock Fusion Algorithms

The Galileo 2017 anomaly episode, affecting both PHM and RAFS units across multiple satellites [43], exposed the limits of primary/backup redundancy and motivated the ONCLE architecture, in which all onboard clocks contribute to a robust ensemble timescale rather than operating sequentially [28]. This approach exploits the statistical diversity of clock noise processes to suppress anomalies without ground intervention [5,28]. Extending this to LEO-PNT constellations of hundreds of heterogeneous satellites—spanning CSACs to space-grade RAFS across dynamically changing inter-satellite link topologies—requires timescale algorithms capable of detecting and isolating anomalous clocks in near-real time [2,12]. The Galileo four-clock architecture [16,36] and ONCLE [28] define the current state of the art; their generalisation to large heterogeneous constellations remains an open problem with direct service-integrity consequences.

8. Conclusions

This paper has surveyed the principles, architectures, and in-orbit performance of AFRs across the major global and regional GNSS constellations, covering GPS, Galileo, GLONASS, BeiDou, SBAS, QZSS, and NavIC. It has additionally introduced the systematic frequency shifts that constrain clock accuracy, and discussed emerging applications of atomic clocks in aerospace systems beyond traditional satellite navigation, with particular attention to the nascent LEOPNT paradigm and spaceborne fundamental-physics experiments.

Three atomic clock technologies dominate the GNSS space segment: the RAFS, the Cs thermal beam clock, and the PHM. RAFS units are the most widely deployed, offering the best compromise between compactness, low power consumption, and long-term stability, underpinning GPS, BeiDou, GLONASS-K, QZSS, and NavIC. The latest generations of space-qualified RAFS units achieve one-day Allan deviation approaching the low 10^{-15} level [3–5]. PHMs provide the best long-term stability at the cost of substantially greater mass, volume, and power demand, and are consequently deployed only aboard Galileo and select BDS-3 satellites [21,22,26]. Cs beam clocks, foundational to the SI definition of the second and maintained as primary fountain standards at national metrology institutes with systematic uncertainty at the 10^{-16} level [8,24], are increasingly confined to ground-based applications. By contrast, Chip-Scale Atomic Clocks (CSACs), orders of magnitude less stable but meeting unique size, weight, and power constraints, are the enabling AFR technology for the emerging LEO-PNT ecosystem [3,11].

Performance comparisons across constellations reveal a clear hierarchy: Galileo PHMs and GPS Block III RAFS represent the current pinnacle of operational GNSS clock stability. BDS-3 clocks are rapidly closing this gap, with the BDS-3 PHM already delivering long-term stability comparable to the Galileo PHM [26,27]. GLONASS remains architecturally constrained by the Cs thermal beam clocks carried aboard its legacy GLONASS-M satellites, though the introduction of Rb AFRs with GLONASS-K1 [3] is progressively narrowing this performance gap [46]. This Cs-clock legacy is not a performance choice but a consequence of technical path dependence: the GLONASS constellation was standardised around Cs thermal beam technology during the Soviet era in the 1970s and 1980s, when that architecture represented the state of the art, and the industrial and qualification infrastructure built around it constrained subsequent upgrade cycles [4]. GPS's own evolution illustrates a contrasting institutional logic: the consolidation to three RAFS units per satellite in Block III, eliminating the mixed Rb–Cs configuration of Block IIF, reflects the maturation of the U.S. Rb supply chain through the Rockwell–Efratom–Excelitas lineage and a deliberate programme decision to accept the RAFS stability ceiling in exchange for reduced per-satellite cost, simplified qualification, and supply-chain continuity over a 15-year operational lifetime [3–5]. Galileo's clock architecture embodies the opposite philosophy: the adoption of PHMs alongside RAFS was an explicit design decision to exceed GPS timing performance rather than match it, positioning the European system as the accuracy leader among operational GNSS constellations and establishing PHM space-qualification heritage through the GIOVE-B demonstration that no other programme had yet accumulated [21,22]. The Galileo dual-technology quadruple-redundant clock architecture stands out as a design philosophy lesson: combining two clock technologies in a four-clock ensemble per satellite provides both technological resilience and the flexibility to select the optimal reference depending on operational conditions [5,16,22].

Beyond MEO GNSS, the LEO-PNT concept is establishing itself as a strategic complement to traditional satellite navigation. The ESA Celeste mission, which successfully launched its first Pathfinder A CubeSats on 28 March 2026 and received its first navigation signal on 8 April 2026, is the most advanced institutional effort to characterise LEO-PNT signal performance across multiple frequency bands [14]. The taxonomy of LEO-PNT architectures proposed by Menzione and Paonni provides a systematic framework for evaluating AFR requirements across each architecture class [9], whilst the strategic assessment by Ries et al. identifies the path toward integrating LEO-PNT into European PNT sovereign capability [10].

The NASA Deep Space Atomic Clock (DSAC) demonstrated that miniaturised trapped-ion technology can achieve long-term frequency stability up to an order of magnitude better than the most capable operational GNSS clocks, validating a new pathway toward autonomous one-way navigation for deep-space missions independent of ground-station communication delays [30,49]. The ESA/CNES ACES mission—launched on 21 April 2025 and installed on the Columbus External Platform Facility of the International Space Station on 25 April 2025 [50]—advances the frontier for spaceborne fundamental-physics investigations, combining PHARAO (laser-cooled caesium clock) and SHM (active H-maser) to test the gravitational redshift predicted by general relativity [3,51]. Together, DSAC and ACES illustrate how the atomic-clock technologies deployed across the GNSS constellations are carried beyond satellite navigation into deep-space autonomy and fundamental-physics experimentation.

Finally, the 1-m positioning precision demanded by modern users translates into a 3-ns timing budget, which in turn sets the accuracy, stability, and environmental-sensitivity specifications for every spaceborne atomic clock. The atomic-clock roadmap surveyed in this paper, spanning from discharge-lamp-pumped Rb AFRs of the 1970s through

space-qualified Rb and H-maser standards to modern CSAC-enabled LEOPNT constellations and spaceborne fundamental-physics experiments, demonstrates that each successive generation of technology has systematically addressed the environmental-sensitivity challenges of its predecessors whilst delivering the sustained stability improvements that underpin satellite navigation as an ever-more-precise and resilient enabling infrastructure.

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